AD NO. 29380
ASTIA FILE COPY

AIR WEATHER SERVICE
TECHNICAL REPORT 105-93

A DESCRIPTION OF SOME METHODS OF EXTENDED-PERIOD FORECASTING

MARCH 1954

HEADQUARTERS
AIR WEATHER SERVICE
WASHINGTON, D.C.

AWS TECHNICAL REPORT
NO. 105-93

AIR WEATHER SERVICE
MILITARY AIR TRANSPORT SERVICE
UNITED STATES AIR FORCE
Washington 25, D. C.

March 1954

FOREWORD

1. General: Air Weather Service Technical Report 105-93, "A Description of Some Methods of Extended Period Forecasting," is published for the information and guidance of all concerned.

2. Scope: It is recognized that skill in extended forecasting cannot be imparted merely by written instructions. Nevertheless, forecasters who have had practical training in an extended-forecast center and those who must use or interpret the extended forecasts made by centers, feel the need for reference material on methods used in making extended forecasts. This report provides a brief description of the various methods or systems of extended forecasting which appear to have any rational meteorological basis; the mean circulation methods currently used by the U. S. Weather Bureau and Air Weather Service are discussed in greater detail. As most of these methods are controversial, no final opinions or decisions on their validity can be made. Evaluations, where given or implied in this report are representative of ones widely believed among reputable meteorologists, but are not necessarily the official views of the Air Force.

3. Additional Copies: Additional copies of this report may be obtained in accordance with AWS Letter 5-3.

BY ORDER OF THE COMMANDER:

OFFICIAL:

Louis W. Berger
LOUIS W. BERGER
Lt. Col., USAF
Adjutant

NICHOLAS H. CHAVASSE
Colonel, USAF
Chief of Staff

DISTRIBUTION:

Hq., AWS 30 copies
Weather Centrals 3 copies
Units and Detachments 1 copy

CONTENTS

A DESCRIPTION OF SOME METHODS OF EXTENDED PERIOD FORECASTING

I. INTRODUCTION

Military planners have long recognized the effects of weather on the optimum operating efficiency of our own and enemy forces. Therefore they desire meteorological data of various types and for differing periods. The mission of the military meteorologist is to provide this weather information.

Climatological analysis is adequate for meeting the great majority of planning requirements. As military planning becomes more detailed, however, the weather advice supplied to operational planners must also become more exact. For nearly all tactical military operations, it is the expected deviations from climatological averages or day-to-day, hour-to-hour changes which are desired. In many cases, such deviations can be forecast.

Proficiency in forecasting varies with many factor including season, geographical location, type of information desired, accuracy of current analysis upon which the forecast is based, and inherent variability of the phenomena. Generally speaking, skill increases as the area increases over which a predicted element is averaged; thus, a prediction of point rainfall is less likely to be accurate than a forecast of the average rainfall over an area of 1,000 square miles. Skill decreases rapidly as the forecast period increases to the point where merely a climatological analysis provides the most dependable answer for the requirements.

Terms such as short-range, medium-range, extended-range, and long-range, have often been used as modifiers to define various forecast periods. Since the term "range" can denote extent in space as well as time, it is easily misinterpreted. The exact period should be used if possible, e.g., 36-hour forecast or five-day forecast. In this report, forecasts covering periods up to 48 hours are called short-period forecasts and those in excess of 48 hours, long-period forecasts. A forecast for a period of the order of magnitude of five days or a week is defined as an extended-period forecast, and it is with such forecasts that the report primarily is concerned.

To the extent that a weather forecast is, in effect, a statement of expected deviations from climatological normals, it follows that the accuracy of a forecast also depends to a degree upon the forecaster's knowledge of pertinent climatological statistics. This principle applies to all forecasts, regardless of period. Since, generally speaking, our ability to forecast weather decreases with an increasing period, predicted deviations from climatological normals will also decrease in accuracy as the forecast period extends.

The perspective of a forecaster must depend on the forecast period. For short periods, he is concerned primarily with the synoptic wind and pressure systems in his immediate vicinity. Over longer periods, he must deal with hemisphere-wide areas and must be concerned with the larger-scale synoptic features and with time averages of maps and individual weather elements. Accordingly, he is faced with the necessity of selecting techniques appropriate for the forecast periods. For example, pure extrapolation of a front is recognized as a successful forecasting technique in very short-period prediction. Such factors as acceleration, frontogenesis, and frontolysis become increasingly significant as the period of the forecast increases. Nevertheless, since there must be continuity and consistency between short-period and extended-period forecasts, the forecaster must be trained with respect to the methods of both ranges. He will find, indeed, that the short-period forecast is often a major factor in the success or failure of prognosticated long-period trends.

Descriptions of a number of long-period or extended-period forecast methods are presented in this report. Although nearly all the methods have some things in common, an attempt has been made to separate them into three broad classifications:

(1) Methods based mainly on statistical procedures and largely unconcerned with map presentations or physical reasoning.

(2) Methods based on types-of-map presentations which are primarily empirical and which make only secondary use of statistical and physical reasoning.

(3) Methods in which physical reasoning plays an important part but in which empiricism and statistics also are used to a significant extent.

Although references are occasionally made to individual long-period-forecasting rules which are not directly related to any of the methods described, it is obvious that the scope of this report does not permit inclusion of all of the procedures mentioned in meteorological literature.

II. STATISTICAL METHODS

Numerous statistical studies have been made in an endeavor to throw light on the problem of long-period forecasting. Research has covered a variety of fields including solar phenomena, polar ice, sea-surface temperatures, the association of weather conditions in one region with contemporary or subsequent weather in some other region, the relationship between weather in one season and the weather of a subsequent season in the same locality, and many other types of trends or relationships.

Statistical techniques provide a means of processing and analyzing large amounts of data in order to determine how certain "interrelationships" operate.

Once these interrelationships have been determined they often given an insight into the underlying physical laws governing these relationships. A brief and necessarily very incomplete description of some of the studies made in the field will be given in this section.

A. Walker's Method.

Sir Gilbert Walker [83-90] studied atmospheric conditions by computing numerous correlation coefficients for points all over the world dealing primarily with four groups of phenomena: (1) relationship of sunspots to weather; (2) relationship between seasonal weather of different regions; (3) the "large-scale oscillations"; (4) rainfall in India.*

1. Sunspots. He published three papers on the correlation between mean sunspot numbers** and contemporary annual values of temperature, rainfall, and pressure at numerous stations throughout the world. These were based upon at least 30 years of data and in many cases a much longer period of records was available. The mean sunspot number was found to correlate negatively with surface temperatures at most stations, with the highest values in India and Southern China (-0.15 to -0.45), southeast Australia (-0.30 to -0.50), parts of South America, and all of North America with the exception of Galveston (-0.05 to -0.35). Walker believed that such correlations were the result of an increased over-all circulation, associated with sunspot maxima. An increased circulation would cause abnormal cloudiness and rainfall which, in turn, would reduce the surface temperatures. Similarly, sunspot maxima could be related to rising temperatures, or at least, to less slowly falling temperatures, in the upper air, over desert areas where cloudiness and rainfall cannot penetrate, and for tropical island stations where lapse rates are usually steep and the air very moist under any circulation. To prove this point Walker cited several low correlations at stations at high elevations, on deserts, and on tropical islands.

Walker not only used rainfall data (from 152 stations) but also considered the water stages of the Nile, the outflow of the Mississippi, the level of Lake Constance, and the volume of the Caspian Sea. An isopleth map showing the correlations between rainfall and sunspot numbers gives very complicated patterns, which are probably due, in part, to the effect of topography. However, Walker considered the correlation in the Nile for the years 1749 to 1800 and the 0.24 correlation in the same area for the years 1865 to 1912, as well as the correlation of 0.20 or less for individual stations in India to be indicative of a relationship between sunspots and rainfall. Perhaps the clearest case was found in South America where rainfall south of 30° Latitude showed a deficiency at five stations during sunspot maxima.

---

*Material for this discussion primarily was extracted from the Report of Work of G. E. Walker by R. B. Montgomery. [45]

**Those referred to in this report are the Wolf-Wolfer Zurich sunspot numbers.

The correlation between pressure and sunspots found by Walker tend to support his theory of increased circulation with sunspot maxima. He concluded, however, that although some relationships between weather and sunspots existed, they were entirely too weak for practical forecasting.

2. Seasonal Weather. In studying the world-wide interrelationships of various weather elements, Walker computed numerous correlations of contemporary and lag relationships between seasonal pressure, rainfall, and temperature. For example, the mean temperature at Capetown, South Africa (December-February) was correlated with the mean pressure for southern South America (mean of Buenos Aires, Cordoba, and Santiago) for the preceding winter, spring, the contemporary summer, and the succeeding autumn and winter. Many of these coefficients were larger than would be expected by chance.

The winter surface pressure at Iceland correlated with the contemporary surface pressure in other areas as follows: Irkutsk plus Eniseisk 0.34, Vienna -0.52, Ponta-Delgada (Azores) -0.54, Charleston -0.32, Tokyo -0.38, and Cairo -0.42. The probability that pure chance would produce these correlations at Vienna and the Azores is only 11 in 100,000. These and similar correlations led to the discovery of three "oscillations": The North Atlantic, North Pacific, and Southern. The term "oscillation" refers to the tendency for pressure in one region to vary in a reverse sense to that in another region (i.e., a rise in one region means a fall in another).

3. Large-scale Oscillations. The North Atlantic Oscillation refers to the tendency for subnormal pressures near Iceland to be accompanied by pressure above normal near the Azores, and vice versa. The North Pacific Oscillation denotes the inverse relationship between the Aleutian low and the Pacific high-pressure belt to the south. The persistence tendencies of these oscillations appear too small to make them significant for seasonal forecasting.

The Southern Oscillation refers to the inverse relationship between pressures in the South Pacific and those in the Indian Ocean area. The persistence tendency of this oscillation is very great as shown by the following correlation coefficients between the successive seasons:

December to February with March to May	0.68
March to May with June to August	0.62
June to August with September to November	0.82
September to November with December to February	0.90

Correlations with the Southern Oscillation of previous and subsequent conditions are shown in Figure 1. Port Darwin pressure apparently exercises more control over distant regions on both a contemporary and lag basis than any other world factor. This Southern Oscillation has been used for forecasting rainfall for Japan and Java.

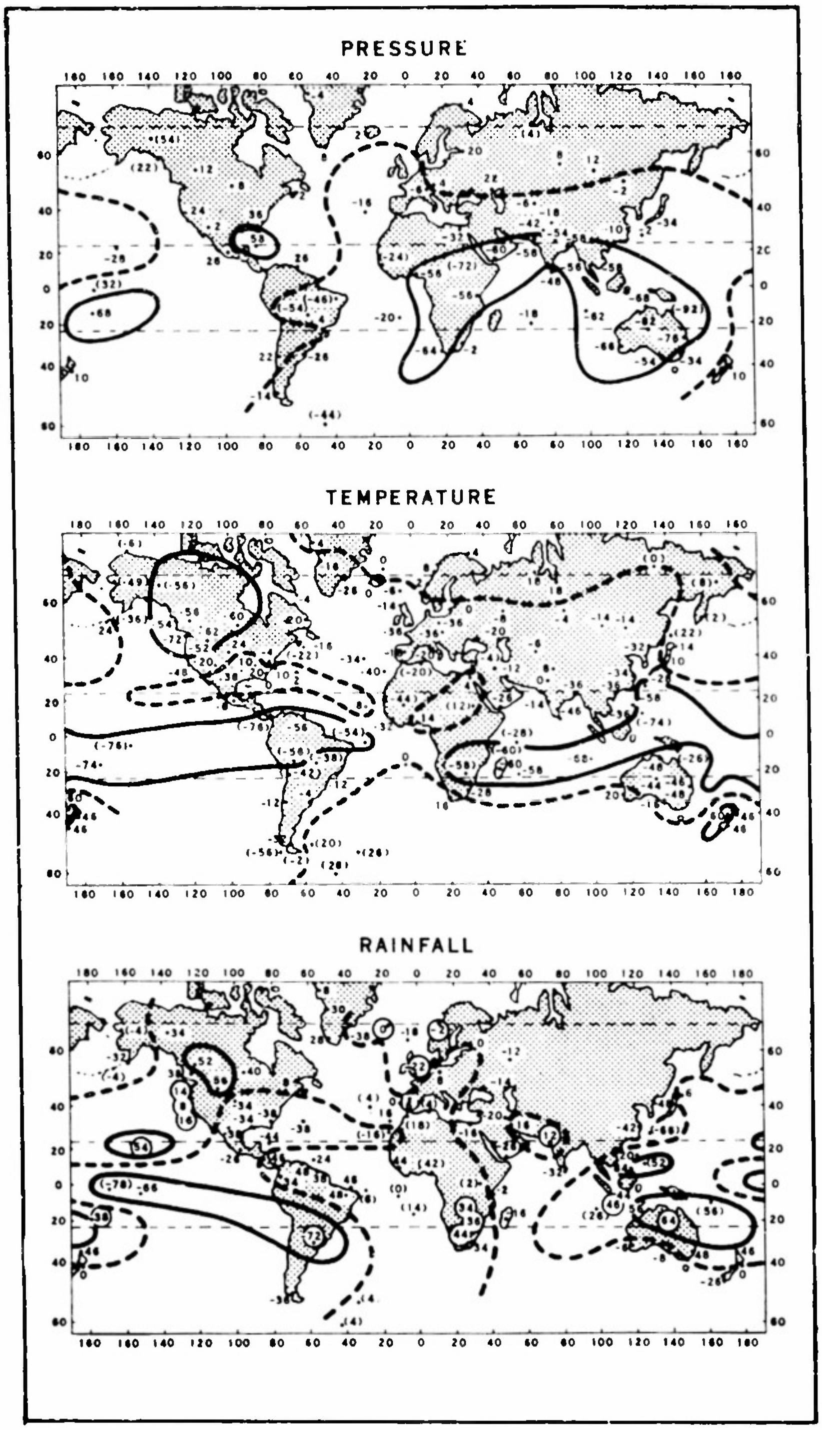


Figure 1. Correlation of Southern Oscillation (June-August) with pressure, temperature, and precipitation during the following winter (December-February). (Walker [83])

4. Rainfall in India. A specific application of world-wide correlations was made in forecasting seasonal rainfall for India. A regression formula, giving a multiple correlation coefficient of 0.76, was developed in 1908 and revised in 1919 and 1924 to predict the rainfall in India during the wet season (June-September) from the variables in Table 1.

TABLE 1

Variables Used to Forecast Rainfall in India
During the Wet Season

Place	Variable	Preceding Month or Months	Correlation
Capetown	Pressure	September-November	-0.38
Southern South America (mean of Buenos Aires, Cordoba, and Santiago)	Pressure	April-May	-0.44
Dutch Harbor	Temperature	December-April	-0.38
Java	Rain	October-February	-0.36
Zanzibar	Rain	May	-0.42
Southern Rhodesia	Rain	October-April	-0.50

Montgomery [45] verified similar formulas by Walker and found that they showed only a slight amount of skill on independent data. He concluded, nevertheless, that the Southern Oscillation should be studied for possible application to seasonal forecasting for North America.

B. Abbot's Method

Abbot's method of extended-period forecasting is based on the following premises [1]:

1. There is a real day-to-day variation of the solar constant.

2. These solar variations comprise 12 or more periodicities, all of which are integral submultiples of 23 years.

3. Corresponding periodicities occur in temperature and precipitation at terrestrial stations. Abbot believes that these weather periodicities are the direct result of periodicities in solar radiation and are sufficiently well defined to serve as the basis for detailed extended-period forecasts. For example, he

currently issues forecasts of day-by-day weather in Washington, D. C. for a period one year in advance on the basis of an assumed cycle of 27.0074 days in precipitation [2] and 6.6456 days in temperature [3].

Numerous objections have been made to Abbot's methods. In the first place, the observed variations in the solar constant are so small (less than 1 percent of average value) that they could be fictitious and caused by errors of measurement (MacPherson [42]). It also is difficult to see how such small solar variations could cause large-scale weather changes. Furthermore, Abbot himself has noted [1] the existence of major changes in the form, phase, and amplitude of solar and weather periodicities, which make their use extremely complicated and difficult. Finally it should be noted that the solar and weather periodicities found by Abbot have been subjected to rigid statistical tests by Page [61] and by Smagorinsky and Brier [75]; in each of these tests it was concluded that the reality of the alleged periodicities was extremely doubtful.

C. Schell's Method.

The method proposed by Schell [73] is essentially an extension of the work of Sir Gilbert Walker. It is based on what Schell calls "dynamic persistence". By his definition this is the persistence, in certain areas, of sea-level pressure averages which affect subsequent weather in distant regions where such persistence is non-existent.

The effects of "dynamic persistence" are most notable in areas whose weather is correlated with an earlier sea-level pressure value for tropical Australasia. This value is obtained by averaging the simultaneous sea-level pressures at Manila, Port Darwin, Batavia, and Calcutta. Australasian sea-level pressure is very persistent from fall to winter as indicated by a coefficient of serial correlation of 0.77 based on 54 years of data. Schell claims that many of the storms which originate in this area cross the Pacific ocean and enter North America. Hence he hypothesizes that a subnormal sea-level pressure value in tropical Australasia is followed by excessive storminess and precipitation in North America. This relationship, based on data from 1895-1940, is illustrated in Figure 2, which shows the correlation between Australasian autumn pressure and U. S. winter precipitation.

The large area of negative correlation in northwestern United States is in support of Schell's hypothesis. The large positive area in the southeastern United States is due to the existence of an inverse relationship between storminess and precipitation in the northwestern and southeastern United States. Intermediate areas show little correlation since they may be affected by storms from either the Pacific Ocean or the Gulf of Mexico. Schell incorporated these relationships into simple regression equations which showed some success in forecasting when tested on the years 1940-1945.

Schell gives three other examples of the occurrence of "dynamic persistence". The most impressive, perhaps, is the relationship between February and March temperatures in northern Europe and the average pressure gradient in that area during the preceding month, as illustrated in Figure 3.

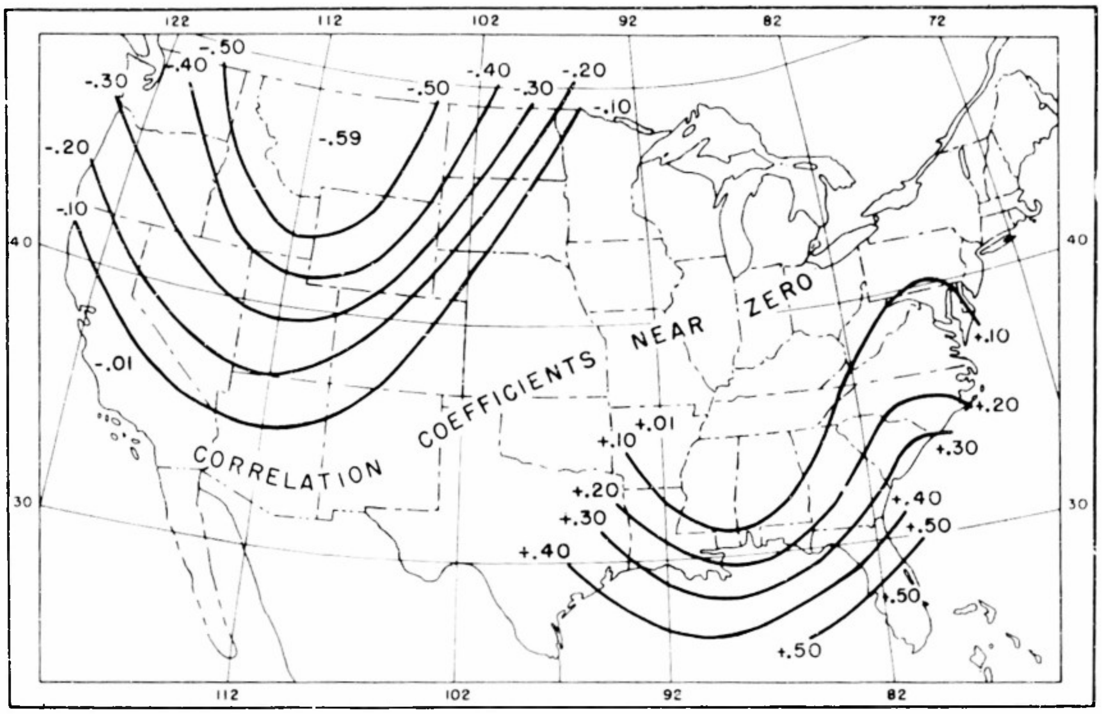


Figure 2. Correlation between sea-level pressure in Australasia during the period September through November, and precipitation during the following winter in the United States. (Schell [73])

A second example is the relationship between pressure at Port Darwin, Australia, from August to October and rainfall in the following November in the southern East Indies, as indicated by a correlation coefficient of -.56 for the period 1881-1940. The third relationship is the tendency for a southward displacement of the Greenland Sea ice during April-July to be followed by a southward displacement of the cyclone track in Europe during October, November, and December. This results in an increase of precipitation in England and a decrease of precipitation in northern Norway.

It should be recognized that such statistics are valuable in indicating areas where lag relationships are most pronounced. The physical mechanisms which cause the correlations are not clear, however, and the applicability of the method may be limited to a small number of regions and seasons for which reliable prediction formulae can be found. More research is required before the useful scale of such techniques can be determined.

D. Clayton's Method.

H. H. Clayton's method of long-range forecasting is based on the belief that changes in temperature and pressure in all parts of the world have an intimate relation to changes in solar conditions. (See Figure 4a and 4b.) The theory may

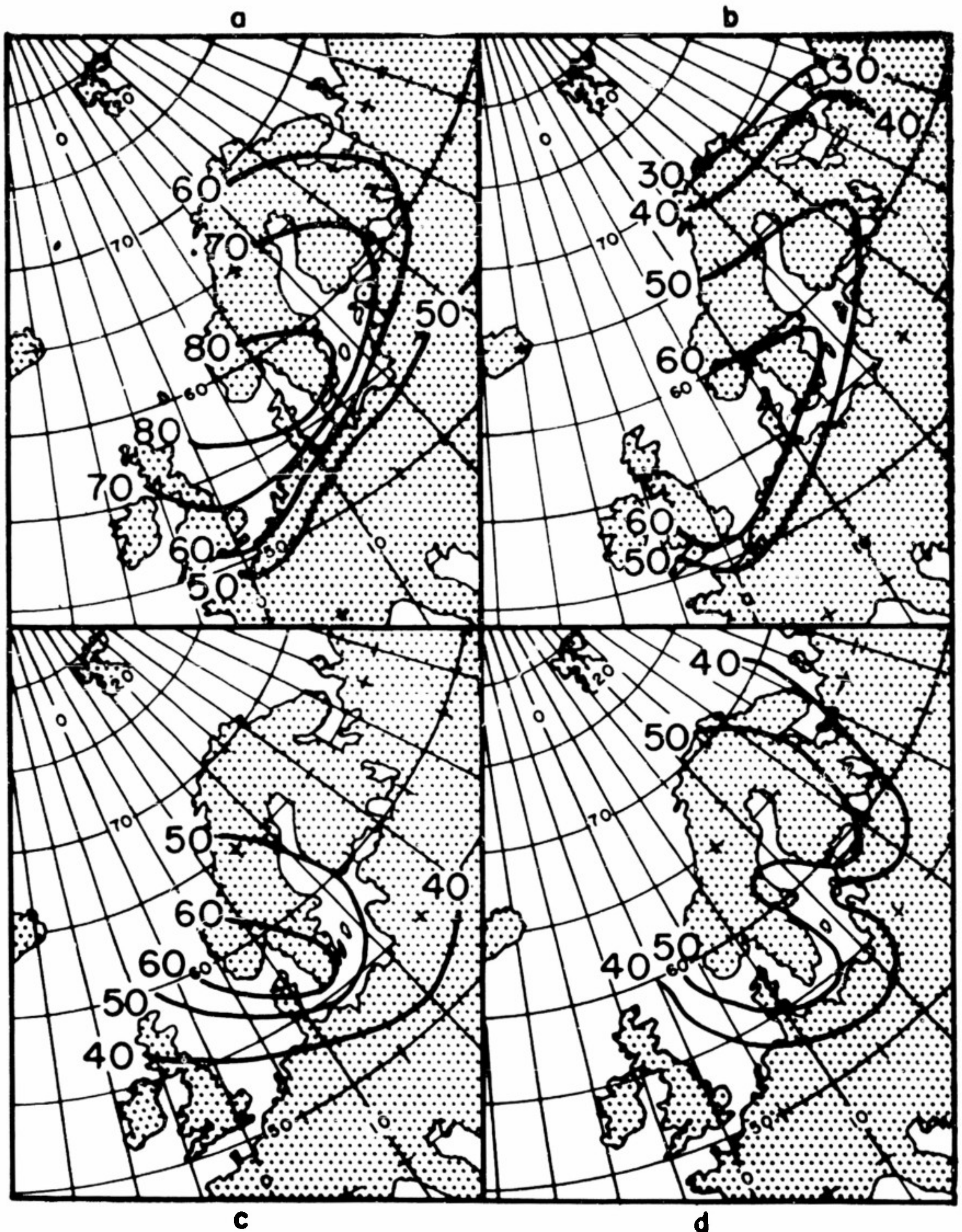


Figure 3. Relationship of the monthly temperature of northern Europe to the monthly circulation, shown by correlation coefficients, r, (1881-1944). "Circulation" is represented by the departures of pressure at Stykkisholm and Vardo subtracted from that at Zürich.

a: February temperature vs. February Circulation.
b: March temperature vs. March Circulation.
c: February temperature vs. January Circulation.
d: March temperature vs. February Circulation. (Schell [73])

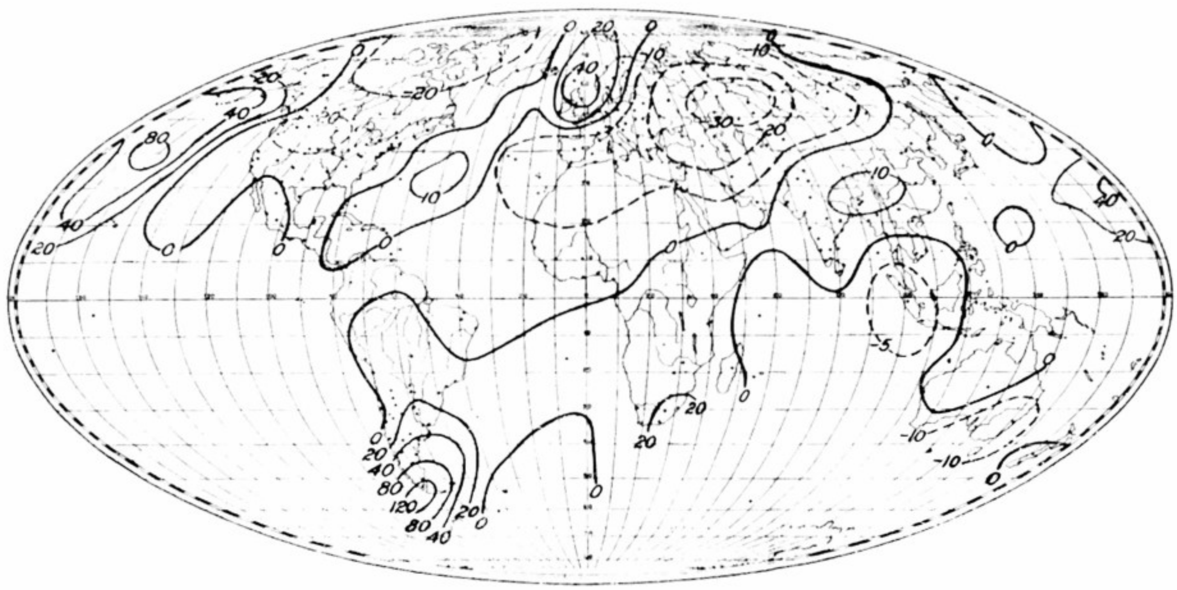


Figure 4a. Departure of pressure at time of maximum of solar radiation in 11-month period, in units of 0.01 millimeter.

Figure 4b. Departure of pressure at time of minimum of solar radiation in 11-month period, in units of 0.01 millimeter.

be summarized as follows [21]:

"With an increase of solar radiation, the temperature rises and the pressure falls in equatorial regions. This is immediately followed by a rise of pressure and a fall of temperature in temperate regions reaching a maximum between latitudes 40 and 60 degrees north and south. From the region of maximum rise of pressure, a wave of returning pressure starts towards the equator but also drifts eastward with the eastward drift of the atmosphere. These waves are believed to be the cause of the waves of temperature and pressure observed at various stations throughout the world." Clayton claimed that this relationship between changes in solar radiation and subsequent changes in weather applies not only to periods of a few days' duration but also to periods of a month, a season, a year, a decade, and a century.

There are five steps in Clayton's forecast procedure [22]:

1. The weather phenomena of temperature, pressure, and precipitation are analyzed by smoothing data measuring these parameters into pulses, waves, or periods of successively increasing length. This is done for each station in a network of stations. (The latest values of the phenomena may be plotted on maps and lines of deviation from the smoothed data drawn. From a succession of such maps, the movement of areas of plus and minus departure can be followed and their future position anticipated.) However, the process Clayton favored is continued in the following steps.

2. Solar radiation data are smoothed into pulses and waves in the same manner and these pulses or waves are correlated with the meteorological pulses or waves.

3. The latter waves are projected into the future using for the extrapolation the mean length of a solar period determined by experience or calculation. This is done for a succession of periods of different lengths.

4. The values for a particular time desired are read from each of the curves so projected ahead and the forecast values are added together to obtain the expected value at that station.

5. The process described in Step 3 is performed for a network of stations, the sums are plotted on maps and lines of equal value drawn. The result is a prognostic map of the expected occurrence for the valid time from which forecasts for any area may be inferred as required.

In addition to using solar-constant variations, Clayton has also made extensive use of possible relations between weather and the sunspot cycle. The relations were recently tested by Wexler [97], using data based on the 40-year historical map series, but no conclusive results could be obtained.

The validity of Clayton's forecasting method has been subjected to severe criticism by Willett [98], Page [61] and others. They claim that periodicities in Clayton's data are the result of his method of smoothing and not due to real periodic variation in the original data. Furthermore they question the reality of changes in the Smithsonian solar constant data used by Clayton in view of MacPherson's [42] conclusion that "any real variations of the sun are completely masked by

errors of measurement, both instrumental and atmospheric." It also is apparent that the physical basis of Clayton's method may be insecure. Finally, it should be noted that Page verified five quarterly forecasts made by Clayton for 1936 and 1937 and concluded that the forecasts had no real skill. For these reasons Clayton's method has never been generally accepted by meteorologists.

E. Statistical Studies Applied to the United States.

Over the past 50 years, numerous statistical studies on lag relations, anomalies, etc., have been conducted by various meteorologists. Brief fragments of some of these studies will be noted here to illustrate the types of statistical studies that have been conducted for the United States.

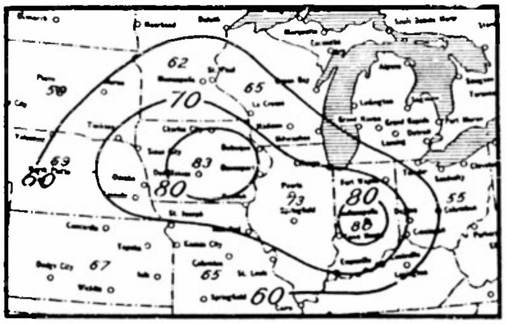
Bliss [10] presented four correlations dealing with mean winter temperatures for central North America and earlier conditions over the Indian Ocean. He found that the mean summer pressure at Mauritius correlated +0.40, autumn temperature at Batavia +0.54, Nile flood water stage during summer -0.40, and the Indian summer Monsoon rainfall -0.46 with the succeeding mean winter temperatures over central North America. Weightman's [96] correlations between the Indian Monsoon and subsequent mean winter temperatures over northern and western North America substantiate the inverse relationships between the Indian Monsoon and subsequent temperature anomalies over North America.

Groissmayr [32] found the mean winter temperature at Winnipeg to be an indicator for the temperatures of the following spring in the Great Lakes region and in the North Atlantic States. He reported that in 15 extreme cases from 1874 to 1923 in which the average winter temperature deviated $\pm 7^{\circ}$F or more from normal, the following combined March and April temperatures in the Lake Region and throughout eastern United States, were similarly abnormal. He also correlated Argentine pressure with U. S. temperatures six months later [31], and with many similar variables.

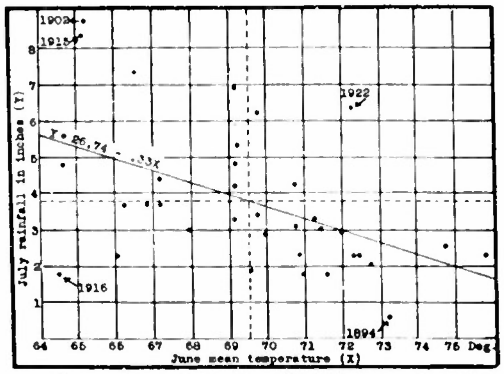
Day found, in an unpublished study, that during a period of 60 years, temperature anomalies of $\pm 7^{\circ}$F occurred at Chicago in 13 Januarys, and that 12 of these cases were followed by temperature anomalies of the same sign in February. Similar but slightly less persistent relationships were found for December and January. Such results suggest that major wintertime controls for abnormal weather conditions are established during the early winter and exert influence for at least two consecutive months. The closer relationship between January and February appears to be due, in part, to the influence of the existence or nonexistence of January's snow cover on February temperature.

Weeks [93], in working with the 155-year temperature records for Baltimore and Philadelphia, found probabilities ranging from 78 to 80 percent for winters with mean temperatures four percent or more above average to be followed by warmer than normal summers. Similarly the probabilities of 78 percent at Baltimore and 64 percent at Philadelphia were found that these summers would have subnormal precipitation.

Weber [92] noted the apparent inverse relationship between mean surface pressures in Alaska in October and mean temperatures during November and December in the Eastern United States. Reed [64] found numerous relationships between temperature in June and subsequent rainfall in July for Iowa and surrounding states (see Figure 5). Somewhat related research has been conducted by Wahl at the Air Force Cambridge



—Figures near the center of each State show the percentage frequency that dry Julys follow warm Junes



—The sloping line is the regression or prediction line, broken lines, mean temperature and mean precipitation. A warm June is 83 per cent indicative of a dry July in Iowa, the most notable exception being 1922

Figure 5. Relationship between temperature in June and subsequent rainfall in July in Iowa and surrounding states. (Reed [64]) In the left figure numbers near the center of each State show the percentage frequency that dry Julys follow warm Junes.

Research Center with primary emphasis on the use of contingency tables in predicting future precipitation and other elements from the past records at a station [106].

McEwen [100] at the Scripps Institution of Oceanography, found significant relationships between ocean temperatures and seasonal precipitation in California, but attained little success in the development of a practical forecasting formula involving these variables. Somewhat allied studies were conducted for the region just south of Iceland. Here the average summer (June-August) water temperature was correlated with quarterly values of Walker's North Atlantic Oscillation. The correlation was higher (negatively) between the water temperature and the Oscillation one and two quarters earlier than with the Oscillation one or two quarters later. This suggests that the summer water-temperature has no effect on the following circulation but that the winter and spring general circulation does affect the following summer water-temperature. (See [62] for an analogous study for Canada.)

Weightman [96] computed correlation coefficients between values of temperature and precipitation in the United States and Walker's three Oscillations, and between weather elements at numerous other foreign stations and those in the United States. He found several contemporary and lag relationships, which provide additional evidence of world-wide weather connections. Unable to advance physical reasons as to why such correlations exist, he suggested several avenues of attack which he deems necessary before such statistics can be applied generally to forecasting. He believes that no simple solution to extended-period forecasting is likely unless further knowledge is obtained of the physical explanations of the statistics.

Numerous statistical analysis have been conducted at the Massachusetts Institute of Technology under the supervision of Wadsworth [81] to investigate the application of machine statistical techniques to extended-period forecasting. An investigation was made to determine the predictability of the eastern lobe of the sea-level Pacific anticyclone which is basic to forecasting by the North American type method. It was found that although there was a certain amount of skill in predicting the position and intensity of this cell, only 45 percent of the variability for a forecast of the mean value for the next month and 60 percent of the variability for the average value of the next week were predictable. The results of this study also showed that the Pacific anticyclone does not - in the final analysis - significantly control the pressure distribution over the United States. Other tests, made to see if the Pacific high, in conjunction with the Azores-Bermuda high and the Aleutian and Icelandic lows, operates in some predictable fashion, gave much better statistical results. Numerous correlations of cross products were computed in order to study the possibility of predicting station pressures, temperatures, dewpoints, etc., by means of the past record of a particular station and its relationships with those of other stations comprising a large network covering the United States and Canada. Certain periodicities in pressure values at some localities or between pressures in different localities also were investigated, but none was found to exist as far as individual stations were concerned.

Stationary, non-periodic time series, which consistently explained a stable proportion of the total variability were found. These can be used most advantageously for short-range forecasting, since the predictability drops off very rapidly in time, reaching zero at the end of 72 hours.

An approach similar to that of Wadsworth was applied to the upper-level charts by Bundgaard [78], who developed a method of prognosticating 500-mb charts by a statistical extrapolation of the present contour pattern based on the development of that pattern during the previous 10 days.

F. Symmetry-Point Method.

The symmetry-point method of forecasting was proposed by L. Weickmann [94, 95], after he found that certain oscillations of pressure in the atmosphere are periodic or quasi-periodic in nature, with 72 days and various harmonics of this interval being the most frequent periods of oscillation. A symmetry point is defined as occurring on a pressure graph when the curve repeats itself approximately in reverse order from this point onwards (see Figure 6). The similarity between the curve and its reflected image appears to exist mainly in the broad features and does not generally extend to the smaller details of the pressure curve. "Inverse symmetry," in which a low in the "reflected" half of the curve corresponds to a high in the first half and vice versa also may occur [82]. Weickmann first determined the oscillations and symmetry points by means of Fourier analysis, - symmetry occurring when the crests on troughs of all constituent waves of significant amplitude coincide and inverse when their null points agree. He finds for example, that the main winter symmetry point at Leipzig occurs at the end of December or beginning of January and sometimes persists for many months. The date and the predominant wave length will vary from year to year.

In practice the mean sea-level pressure of about 10 stations located within

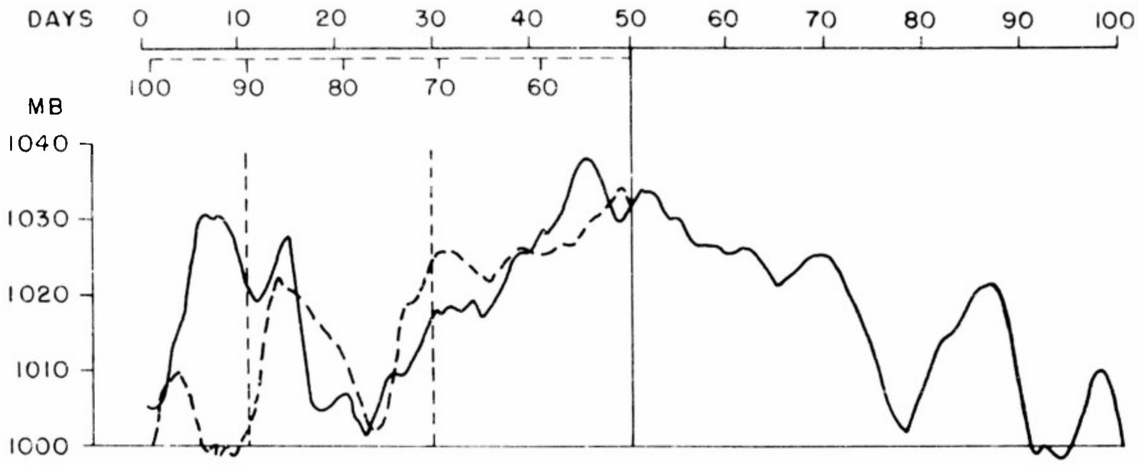


Figure 6. Example of symmetry point in pressure curve. Dashed lines represent reverse image of pressure curve after the symmetry point (50th day).

an area approximately 500 kilometers square is plotted day-by-day on graphs which are then copied on transparent paper. By turning the paper over, the forecaster gets a mirror image and tries, with the help of the original graphs, to locate by inspection a point of symmetry. Cases of inverse symmetry, where the tissue paper must be folded along a horizontal line to depict a mirror-image, also are sought. Once a symmetry point is found forecasts can be made by copying those portions of the observed curve which are expected to be reflected in the future.

It is obvious, of course, that the utility of this method of forecasting depends on the precision with which symmetry dates can be identified and predicted, and on the degree of resemblance between the pressure graph prior to the symmetry data and its reflected image [82]. During World War II, investigations of the symmetry-point approach also were made in Britain by Walker and Brooks [91], and in the United States by Haurwitz [34]. Both of these groups reported comparable results which were summarized by Haurwitz as follows:

a. The phenomenon of symmetry occurs often enough to be utilized in forecasting, providing it can be recognized upon its arrival.

b. Symmetry does not occur more frequently than it would in a series of terms with normal frequency distribution and a random order. Hence, it seems unlikely, although not entirely impossible, that a method of predicting symmetries can be evolved.

c. Symmetry shows little tendency to persist, hence it cannot be utilized for forecasting by the time it is noticed in a pressure graph.

The symmetry-point method also has been severely criticized by Baur [8], who says that two years' work at his Long-range Weather Forecasting Institute on computing

correlation coefficients for pressure values paired on opposite sides of symmetry points as defined by Weickmann failed to produce enough results of forecasting significance to justify continuance of the method. It must be remembered, however, that correlation coefficients afford no means of allowing for slight displacements in time of events and that high values were hardly to be expected even in cases where the symmetry is deemed to be good by other standards of assessment. In the appendix to his book, Baur [8] shows by actual experiment that by selection of numbers in a manner which imposes a degree of serial correlation (persistence) corresponding to that observed in weather data, one obtains series which contain periodic variations, and even symmetry points and symmetry correlations, that are almost identical with those found in series of daily pressure observations. Baur believes that the great variety of periodicity and symmetry patterns which may be derived from pressure series are primarily the incidental result of serial correlation in the data, and as such have no greater forecasting significance than the persistence itself.

Baur [9] also points out that the existence of a symmetry series can be detected with some degree of certainty only if about 20 days of the symmetry series have elapsed. Even within a "very good" symmetry series no reliable conclusion can be drawn from a 20-25 day "sample" as to whether and how long the reflected curve of the pressure will persist - assuming the symmetry-point date was accurately forecast. For example, the symmetry point for the pressure curve of Potsdam on 26 December 1932, may be cited. The correlation coefficient between corresponding days from the 1st to the 25th day before and after the symmetry point was +0.75; from the 26th to the 50th day before and after it was -0.46.

From the above findings it can be concluded that even if symmetry points exist their use is at best quite subjective and as yet impossible to express in a quantitative form suitable for testing. There are many meteorologists who doubt the reality of symmetry.

G. Singularities Method.

A "singularity" is defined as a certain weather phenomena that recurs at approximately the same time nearly every year. References to these recurrences are echoed throughout the folklore of all countries under such titles as Old Wives' Summer, Indian Summer, January Thaw, etc. These popular beliefs were ignored by meteorologists until Alexander Buchan wrote his famous paper in 1869 on "Interruptions in the Regular Rise and Fall of Temperature in the Course of the Year" [18].

Since Buchan's time, and particularly in the last 20 years, many papers have appeared in the literature, advancing arguments that some weather types occur more regularly than can be expected on a chance basis. Most notable of these are numerous studies by A. Schmauss [74] and others [e.g., 29, 101] in Germany. Recently C. E. P. Brooks of Great Britain [16, 17] and French meteorologists [108] have seriously examined the matter for its forecasting possibilities. Singularities in the frequency of synoptic weather patterns are also being used to some extent as an aid in extended-period forecasting in Germany [9, 101].

Singularities can be studied with respect to practically any discrete meteorological phenomenon. The usual method is to establish the average daily, 5-daily, or

weekly values of an element over a large number of years. When these values are plotted for the successive days or pentads, etc., of the year, one notes that the resulting "graph" presents a number of maxima and minima which are clearly accentuated in relation to the other irregularities of the average curve (see Figure 7). It is the contention of most students of singularities that such irregularities when sufficiently pronounced are real and would not be smoothed out by addition of many more years of data. If such is the case, singularities may be considered as the average fixation of weather to calendar dates which gives a "natural" division of weather regimes within each season. One argument in favor of the existence of certain singularities is the fact that comparisons of works of the independent investigators, and of data from various stations show the same results.

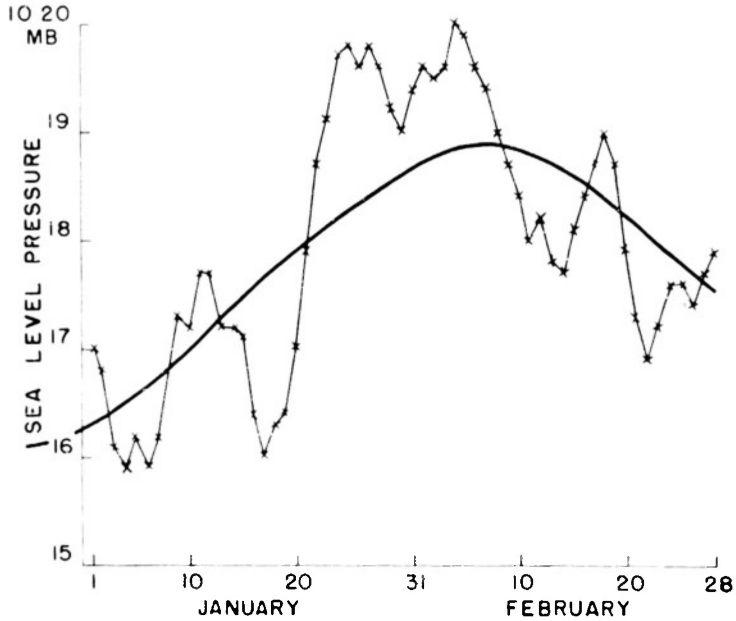


Figure 7. Five-day mean sea-level pressure at 50°N 85°W during January and February. (Computed using five-day moving averages for 40 years of data, 1899-1939). Smooth curve computed using bi-monthly averages of sea-level pressure.

Some criticism has been given of the tendency (especially in Germany) to assume that all the irregularities in the curves are singularities; it has been shown by Bartels [105] that most of these are produced by purely random processes. Only the larger ones can be taken as real, and careful statistical technique must be used to discriminate them.

The French National Meteorological Service currently is attempting extended-period forecasts (up to 30 days) based primarily on singularities. The service has computed, for many stations, the annual curves of average daily pressure calculated for several 30-year periods, and smoothed by use of five-day moving averages (a five-day mean of observed pressures centered around each successive day of the year). These "base curves" show certain irregularities (singularities) which are superimposed upon gradual seasonal trends.

A similar plot of mean pressures for the past several months is smoothed by the same method, drawn up on a scale suitable for rendering its variation similar in amplitude to those of the base, and plotted on a tissue. This year's curve is superimposed on one of the normal "base" curves, and a match is found nearest the current data. This approximate match is based chiefly on the positions of troughs and ridges in the curves, with less consideration of the amplitude. Thus parallelism is the chief indicator of singularity, and a slight sliding of the time scale is considered permissible in finding the singularities. There is an allowable limit to the number of days by which the time scale can be shifted. A singularity can not enter into the regime of others under the same sign. For example, if pressure maxima are spaced one month apart on a section of the base curve, it is evident that the shifts of the individual singularities can not exceed 15 days on both sides of their average position (mean value of the shifts: ±4 days).

The singularities having been identified, individual five-day (pentad) mean curves are extrapolated more or less parallel to the normal curve, but the amplitudes are exaggerated or suppressed according to the current year's behavior relative to normal. In addition homologous curves ("analogues") are sought for in the recent past (preceding months) as well as symmetries of the larger periods in the curves of pentadal variation. This procedure is followed for several points in Europe and the eastern Atlantic in making an extended-period forecast of the surface pressure or of the surface pressure change. From these points a series of prognostic sea-level pressure charts is constructed, one for each successive "phase" of the forecast period, and thereby the evolution of the synoptic patterns is portrayed. The forecast values of the temperature, precipitation, clouds and wind are inferred from these maps.

C. E. P. Brooks [17], using a different attack, obtained "singularity dates" remarkably similar to those of other European investigators. His research was directed not so much at finding recurrences of individual climatic elements as at finding recurrences in certain types of weather patterns especially those associated with abnormally high or low pressure (which had been studied by Weickmann's students also).

In addition he examined the distribution of pressure in the region of the British Isles day by day on synoptic charts of 52 years. Each day was placed into one of three categories: stormy, anticyclonic, or unclassified. A stormy day was defined as one on which the pressure over or very near the British Isles was below 992 mb and an anticyclonic day one on which the curvature over the British Isles was anticyclonic and pressure 1020 mb or greater.

Since the object of Brooks' study was to investigate spells of weather, transitory wedges of high pressure or anticyclones covering the area for less than three days were not considered, and a break of one or two days in a stormy or unsettled period was also ignored. Pressure singularities were then selected, partly from the peaks of frequency of anticyclonic, stormy or unclassified days. It was found that these two indications usually agreed within a day or two. The synoptic "succession" was then examined independently in the series of surface-pressure charts of the individual years and in those of the 20-year means to find out how each singularity began, developed, and ended, and to fit the weather changes associated with each singularity into the picture formed by the normal development of the pressure distribution (Table 2). A casual glance at the table might cause one to wonder if the wide scatter of dates of beginning and ending would rob them of any real

TABLE 2

List of "Singularities" in Europe

Singularity	Beginning Date			Ending Date			Occurrences in 52 years	
	First	Mean	Last	First	Mean	Last	No. of Years	Frequency at Peak Date
Early January, stormy	*	Jan. 5	Jan. 18	Jan. 6	Jan. 17	Jan. 22	45	31, Jan. 8
Mid-January, anticycl.	Jan. 7	Jan. 18	Jan. 23	Jan. 17	Jan. 24	Jan. 30	45	18, Jan. 20–21
Late January, stormy	Jan. 18	Jan. 24	Jan. 31	Jan. 24	Feb. 1	Feb. 24	44	31, Jan. 31
Early February, anticycl.	Feb. 1	Feb. 8	Feb. 15	Feb. 6	Feb. 16	Feb. 28	29	22, Feb. 13
Late February, cold spell	Feb. 16	Feb. 21	Feb. 23	Feb. 22	Feb. 25	Mar. 3	22	21, Feb. 22
Late February and early March, stormy	Feb. 11	Feb. 26	Mar. 9	Mar. 1	Mar. 9	Mar. 30	46	32, Mar. 1
Mid-March, anticycl.	Feb. 27	Mar. 12	Mar. 19	Mar. 12	Mar. 19	Mar. 29	27	17, Mar. 13–14
Late March, stormy	*	Mar. 24	Mar. 29	Mar. 24	Mar. 31	Apr. 11	35	26, Mar. 28
Mid-April, stormy	Mar. 28	Apr. 10	Apr. 15	Apr. 10	Apr. 15	Apr. 26	37	25, Apr. 14
Late April, unsettled	Apr. 19	Apr. 23	Apr. 27	Apr. 23	Apr. 26	Apr. 30	27	19, Apr. 25
June, summer monsoon	May 24	June 1	—	June 6	June 21	June 28	(40)	—
July, warm period	—	July 10	—	—	July 24	—	—	—
Late August, stormy	Aug. 14	Aug. 20	Aug. 29	Aug. 20	Aug. 30	Sept. 3	35	16, Aug. 28
Early September, anticycl.	Aug. 21	Sept. 1	Sept. 6	Sept. 7	Sept. 17	Sept. 30	43	25, Sept. 10
Mid-September, stormy	Sept. 7	Sept. 17	Sept. 20	Sept. 18	Sept. 24	Oct. 3	31	22, Sept. 20
Old Wives' Summer	Sept. 9	Sept. 24	Oct. 10	Sept. 14	Oct. 4	Oct. 16	33	—
Early October, stormy	Sept. 28	Oct. 5	Oct. 10	Oct. 5	Oct. 12	Oct. 30	35	26, Oct. 8–9
Mid-October, anticycl.	Oct. 8	Oct. 16	Oct. 19	Oct. 15	Oct. 20	Oct. 28	35	19, Oct. 19
Late October and early November, stormy	Oct. 11	Oct. 24	Oct. 31	Oct. 30	Nov. 13	Nov. 27	52	31, Oct. 29 28, Nov. 9, 12
Mid-November, anticycl.	Nov. 7	Nov. 15	Nov. 22	Nov. 14	Nov. 21	Nov. 30	34	20, Nov. 18, 20
Late November and early December, stormy	Nov. 9	Nov. 24	Nov. 30	Dec. 4	Dec. 14	Dec. 26	51	25, Nov. 25 34, Dec. 9
Pre-Christmas, anticycl.	Dec. 9	Dec. 18	Dec. 24	Dec. 19	Dec. 24	Jan. 5	29	19, Dec. 19–21
Post-Christmas, stormy	Dec. 19	Dec. 25	Jan. 1	Dec. 25	Jan. 1	Jan. 21	43	35, Dec. 28

*Merged with preceding stormy period.

significance since an alternation of anticyclonic and stormy days at least once a month would be expected. However, although the identification of any given singularity is somewhat subjective, each was found to have well marked individual identification characteristics.

Moreover, Brooks' reports indicate that the larger departures from the average dates are mainly accounted for by unusual persistence of stormy or anticyclonic conditions; and, with the exception of the Old Wives Summer, in no case did a singularity begin more than one day after the average date of termination or end more than two days before the average date of beginning. A comparison of the frequency of occurrence on the "peak" date with the total number of occurrences shows that most of the occurrences cluster closely around the average dates — in only two cases is the peak frequency less than one half the total number of occurrences. The regularity of stormy periods during early and late December is especially noteworthy.

Baur [9] states that on 29 September, as well as on the preceding and following day, certain European anticyclonic situations within the period from 1881-1943 reach a better-than-chance frequency. From 20 September to 1 October, Central Europe has, in 65 percent of all years, a period with little cloudiness, infrequent precipitation, and relatively high midday temperature. Weather of this character (called Old Wives Summer) occurs in high-pressure regions, stretching from west to east, with a zonal circulation over northern Europe and a meridional circulation over eastern Europe.

A preliminary study made in Headquarters, Air Weather Service [108] attempted to find whether the singularities in the 5-day mean pressures at points over the North Atlantic are associated with certain synoptic patterns, or in other words whether there are singularities in the occurrence of particular pressure patterns. The results show that the same singularities found by Brooks [17] in western Europe (see above) exist over the Atlantic. The singularities recurred in about 78 percent of the 40 years studied.

Since it is beyond the scope of this report to include all the developments in singularities, the reader is referred to the many articles on the subject. It might be well to conclude, however, that American investigators, working with machine tabulated data, are in a good position to evaluate the concept of singularities and possibly adapt them to present forecasting methods.

H. Polar Ice and Seasonal Weather.

Independent investigators working with different periods of data have obtained fairly comparable and consistent results in relating polar ice to seasonal weather. Proponents have advanced the theory that a variation in the areal extent of polar ice is a good index to the general circulation because of the persistence tendency and the apparently stabilizing effect of polar ice on large-scale atmospheric processes. Often such a persistent element is capable of reflecting in a simpler form a complex feature such as the general circulation. Unfortunately, reliable indices have not been established due primarily to the scanty measurements of polar ice and its complexity in pattern. Observations in the Barents, Norwegian, and Greenland Seas constitute the most accurate and representative set of data. From these observations the mean position of the ice limit has been established as being on a line extending through the Barents Sea from Murmansk, Russia, to Svalbard

(Spitsbergen), then north of Iceland to the lower tip of Greenland. The southernmost extension of the ice limit (April) may vary several hundred miles from year to year with no apparent correlation between the Greenland and the Barents Sea. "Heavy ice" is the term normally applied when the ice limit is far south of its normal position and "light ice" when the ice limit is far north of its normal position.

A synthesis of the research of the various investigators shows that heavy ice and the associated cold polar water are associated with abnormally high and persistent pressures over the polar regions [15]. The abnormal pressure regime appears to affect the general distribution of pressure and weather elements over large areas of the world. The packed isothermal distribution produced by the southward displacement of cold polar air into the normally warmer oceans appears to establish cyclogenetical fields which result in a southward displacement of the mean storm tracks. For example, Wiese (Vize) [72] reports a diminution of cyclone frequency and a southward displacement of the mean path of cyclones over the North Atlantic in summer, autumn, and early winter following a heavy-ice season (April-July). The average displacement of the cyclone path is 2.9 degrees of latitude in summer and 3.4 degrees in the succeeding autumn for the region 40°W - 50°E. Such displacements during heavy-ice years cause above normal springtime rainfall in Norway, and above normal autumn rainfall throughout the Baltic Coast, Scotland, and most markedly in Southern England. For example, C. E. P. Brooks [16] says, "In spring and summer of a year with much ice, pressure tends to be above normal near Iceland, diminishing the force of our westerly winds. In spring the high pressure tends to spread over the British Isles and Scandinavia giving us a fine, though rather cold season; but for the remainder of the year pressure over the British Isles tends to be below normal and the weather to be wet and stormy. This is especially noticeable in the late autumn and early winter; and some of our most disagreeable wet seasons, notably 1912 and 1918, can be attributed mainly to an excess of ice near Iceland and in the Greenland Sea."

Wiese investigated the relation of springtime ice conditions in the Greenland Sea to the succeeding December and January air temperatures in Europe, and found positive correlations as high as 0.50 in Lower Scandinavia and the vicinity of Poland. He also found correlations of -0.79 between ice conditions (July-September) and subsequent winter water temperatures in the Barents Sea.

Wiese constructed mean circulation maps for heavy and light ice years by averaging pressure throughout large portions of the hemisphere for seven years of heavy and four years of light ice in the Greenland Sea (Figure 8). These maps show abnormally strong pressure gradients from Iceland eastward during periods of heavy ice (in conformity with results of earlier experiments by Brennecke [13]). They also show above normal pressures in the neighborhood of the polar seas, below normal pressures in northern Scandinavia and the Norwegian Sea, and, to a lesser degree, below normal pressures elsewhere throughout Europe and the north Atlantic. In the following autumn, pressures continue abnormally high in the polar seas and low over western Europe, especially the British Isles and northern France. This variation in pressure at various points appears to be associated with the abnormal intensities and displacements of the large centers of action during heavy ice years.

In arriving at a physical-synoptic explanation of Wiese's relationships, Schell [72] states that "the role of polar ice in the atmospheric circulation is probably but a single phase of a more general and inclusive interpretation of the process involved, namely that the variation in ice is the result of the character of the

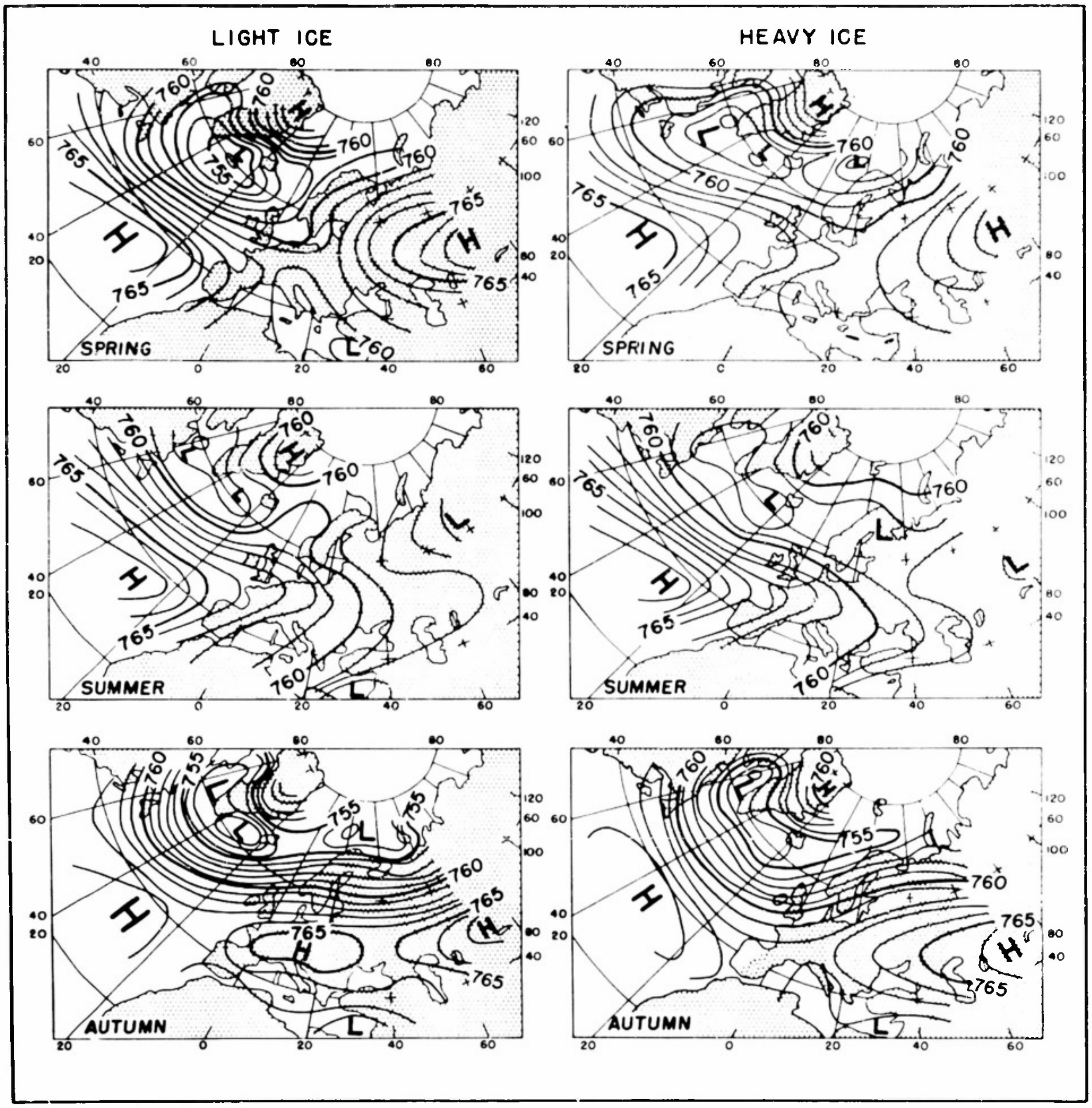


Figure 8. Average pressure (millimeters) distribution for seven heavy- and four light-ice years for spring, summer, and autumn. Ice season, April to July (Schell [72])

preceding state of the general circulation, and that the correlation between ice and subsequent weather.....is due to the reciprocating effect which the ice and cold water exert on the atmospheric circulation."

III. TYPING METHODS

The "type" method of forecasting has been used in many countries since the early history of meteorology [12, 65]. It seeks to classify past observed weather maps into categories or typical situations, and thereby provide a rapid means of selecting cases analogous to the present weather map.

The success of the method hinges on two important considerations:

1. The degrees of skill in recognizing the current type.

2. The ability to forecast its evolution into succeeding types.

Once a type has been accurately recognized, forecasts can be made from idealized daily charts which portray the frontal configurations on successive days of each type and from statistical information on anomalies of temperature and precipitation, predominating air masses, etc.

Often there is good agreement among various forecasters in recognizing the current type when it is a well-marked case, but much less agreement as to the proper identification when the type is one of the numerous transitional or "borderline" cases. In the latter instances, much of the success of the method is dependent on the experience and judgment of the forecaster.

The prediction of succeeding types is much more complicated and probably the weakest phase of the entire weather-type approach. Attempts have been made to determine the statistical probability of one type succeeding another and the relationship of subsequent types to the previous orientation and position of various centers of action.

A. Baur's Method.

1. Five- to Ten-Day Forecasts. The basis of Baur's method of extended-period weather forecasting is his concept of the Grosswetterlage. This term has been translated as the "broad-weather situation" by Sir Gilbert Walker [90] who defined it as "a condition of the atmosphere which controls the weather for several days, remaining sensibly constant in spite of the changes in the latter from day to day. Baur [7] defined it as "the mean pressure distribution at sea level for a time interval, during which the position of the stationary cyclones and anticyclones and the steering within a circulation region remain essentially unchanged." Baur used sea-level pressure data for the years prior to 1933 when there were no daily aerological observations. By requiring constancy of steering, as applied to the motion of isallobaric centers, the pressure distribution in the middle troposphere (5-km level) was taken into consideration.

Neither the temporal nor the regional limits of the Grosswetterlage are rigidly prescribed. The time interval is flexible, depending upon the prevalence of each particular "broad weather situation," but averages about 5 1/2 days in central Europe (Baur, [7]). The Southern Hemisphere similarly has been divided into five sectors. In the circulation region of Europe, Baur [7] established 25 types of

Grosswetterlage which have occurred frequently since 1881. These were grouped into six principal divisions as follows:

1. A high in the Northwest (between Greenland and Scandinavia).

2. A high in the West and Southwest (between the Azores and England).

3. A high on the European continent.

4. A high in the Southeast and South.

5. Cyclonic westerly flow.

6. Low pressure situation.

In a similar fashion Baur [9] has established 16 types of North Atlantic Grosswetterlage, grouped into zonal, meridional, and mixed situations, and seven types of 5-km circulation patterns. In the North American region he accepted the weather type classification developed at the California Institute of Technology [19]. Brezowsky has prepared a revised catalogue of types for use in Europe [6].

The significance of the Grosswetterlage lies in its controlling influence on the weather. Not only are individual cyclones and anticyclones steered by the large-scale circulation pattern, but also local temperature and precipitation anomalies and prevailing air masses. For example, when anticyclonic easterly flow prevails in Europe (Figure 9), the weather is continental in character - dry and cold in winter, dry and hot in summer; in a northerly situation (Figure 10), cold arctic air masses predominate; in a southerly situation (Figure 11), warm tropical flow prevails; and in a westerly situation (Figure 12), moist maritime air masses bring frequent precipitation and much cloudiness.

Having defined the significance of the Grosswetterlage, Baur's principal forecast problem is the determination of its particular type and duration during the coming period. This is achieved through a complex method which is both synoptic and statistical in approach. The method involves study and analysis of the "broad-weather situation" of the day on which the forecast is issued and preceding days, and depends primarily upon the use of multiple correlation tables and analogues.

Baur's method was used in the preparation of 10-day forecasts at the Research Institution for Long Range Forecasts of the State Meteorological Service of Germany which existed from November 1929 until April 1945. The basis of these forecasts, as described by Schell [70], was the calculation of correlations for the past 40 years of sea level data between the mean pressure and the precipitation frequency at selected stations in Germany during the next 10 days as dependent variables, and weather elements of the preceding period at 26 stations in Europe and vicinity, taken in various combinations as well as individually, as independent parameters. The following elements of the past weather were used: mean pressure of the past 10 days, pressure and temperature changes during the past 10 days, pressure changes in the past five days, last daily pressure, and interdiurnal variability of pressure in the past six days. The computed correlation coefficients were plotted on maps, and lines of equal correlation were drawn. The quantities recognized as reliable forecasting factors then were set into multiple correlation tables. Not only did these tables evaluate the relationship between definite values of preceding and following weather, but they also facilitated the selection of days of preceding years on which a weather situation essentially similar to that of forecast day prevailed. For all such analogous days the distribution of the six elements of the past weather mentioned

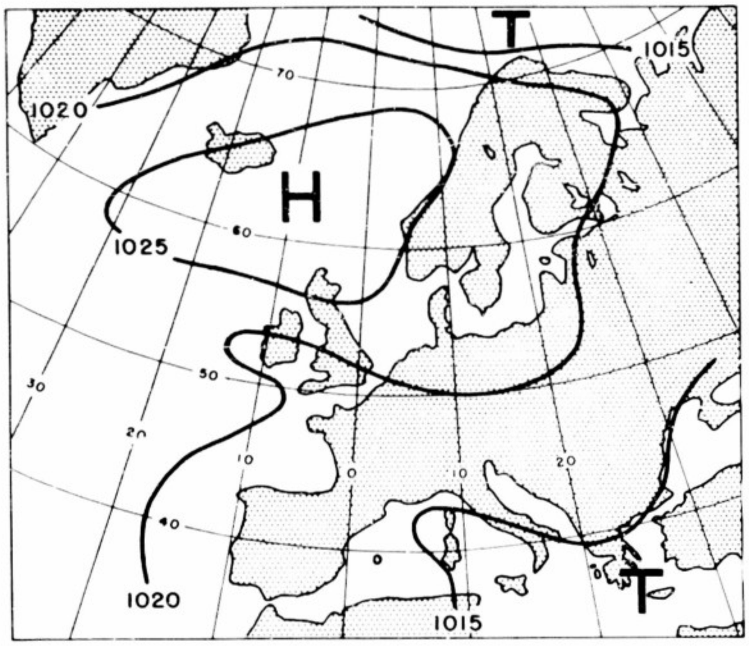


Figure 9. Typical map characterized by a central high over areas between Greenland and Scandinavia with anticyclonic conditions in Central Europe. (Baur [7])

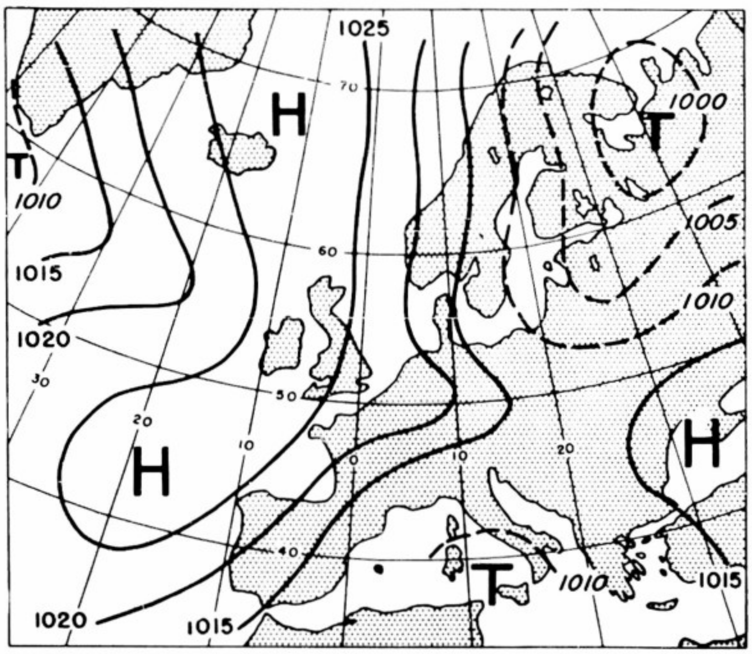


Figure 10. Typical map associated with northerly winds and predominantly cold Arctic air masses over Europe. (Baur [7])

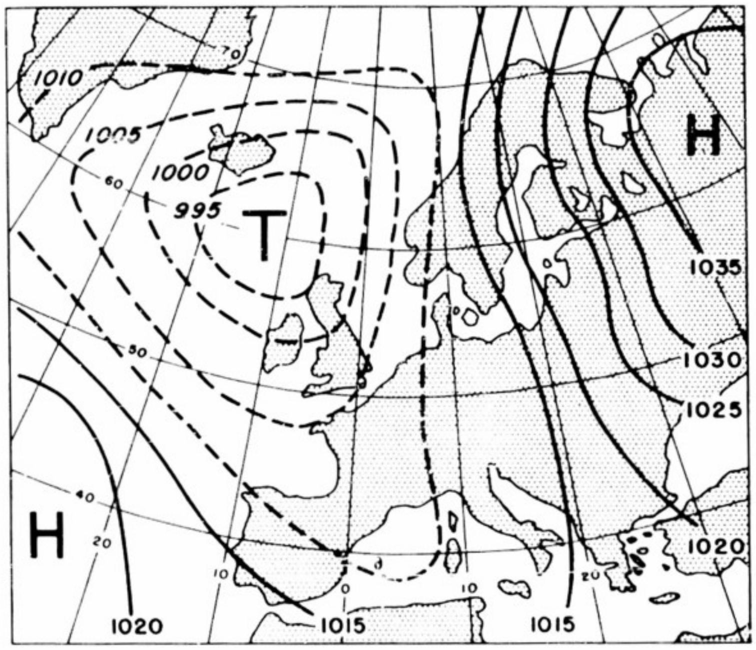


Figure 11. Typical map associated with warm southerly winds over Europe. (Baur [7])

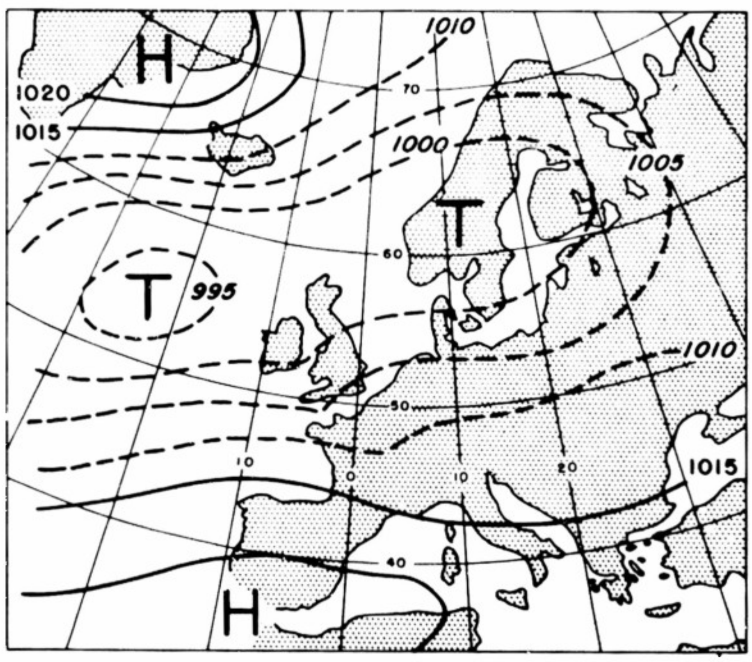


Figure 12. Typical map associated with westerly winds and moist maritime air masses over Europe. (Baur [7])

above was drawn on maps. By comparing these maps with the corresponding charts for the current day the two or three closest analogues were selected. Maps depicting the subsequent weather for these cases were then analyzed in order to determine the most probable current weather development.

The final forecast also was based upon a statistical consideration of such factors as the seasonal frequency of different types of Grosswetterlage, the pattern of the upper air circulation on forecast day, and trends and rhythms during the preceding 10 days. The forecast was worded in a rather ambiguous and indefinite manner as illustrated by the following announcement for the third ten days of July 1935: "The fair prevailingly dry weather of the previous week changed on the 15th to somewhat unsettled weather, but nevertheless on the whole the weather especially in south Germany retained a friendly aspect. This unfriendly but, on the other hand, also not fully settled weather with alternate clearing and short, partly thundery rains will continue for the next few days...."

Verification of Baur's 10-day forecasts for the summers of 1933-36 showed that they had definite skill and were superior to forecasts based on chance, persistence, or the normal (Page et. al. [60]). They had little or no value, however, after the first five days.

2. Seasonal Forecasts. Baur's method for making seasonal and monthly forecasts is based on the assumption that a relationship exists between changes in the atmospheric circulation and the preceding temperature and pressure anomalies over the earth. In order to determine the nature of these time-lag relationships and their physical basis, Baur used both correlation coefficients and synoptic maps. The steps in his procedure are first, a contemporary statistical and synoptic characterization of the element in question; next, determination of the mechanism responsible for the existing relationship; then a study of preceding conditions for clues in predicting the subsequent weather; and finally, the formulation of multiple regression equations incorporating the best individual predictions.

These steps are illustrated by Baur's study of July rainfall in Germany. He found it to be significantly correlated with the contemporary sea level pressure in Europe. Additional correlations with the pressure in India, Greenland, and the Azores were not statistically significant. He then constructed composite maps showing the mean pressure in Europe separately for two wet Julys (Figure 13) and two dry Julys (Figure 14). The pressure distribution in the wet months shows cyclonically-curved west-northwesterly flow of moist air to Germany, while the dry months are characterized by northerly flow and high pressure. Figure 15, giving the difference between the mean pressure in the dry and wet July months, shows that the area of maximum difference is situated over central Europe. It thus substantiates the high correlation noted earlier between July rainfall and contemporary pressure in the same region. Baur's next step was to correlate the July rainfall in Germany with the June pressure and temperature at a large number of stations for a 50-year period. He found that high pressure in northern Norway during the first 20 days of June was followed by low pressure in central Europe during the last 10 days of June, which then persisted or recurred and was associated with heavy rains in July.

These relations may be expressed as the following multiple regression equation: $y = -2.51\ x_1 - 3.13\ x_2$ where y is the departure from the mean July rainfall in mm. in north Germany and x_1 is the mean pressure at Tromso, Norway for 1-20 June.

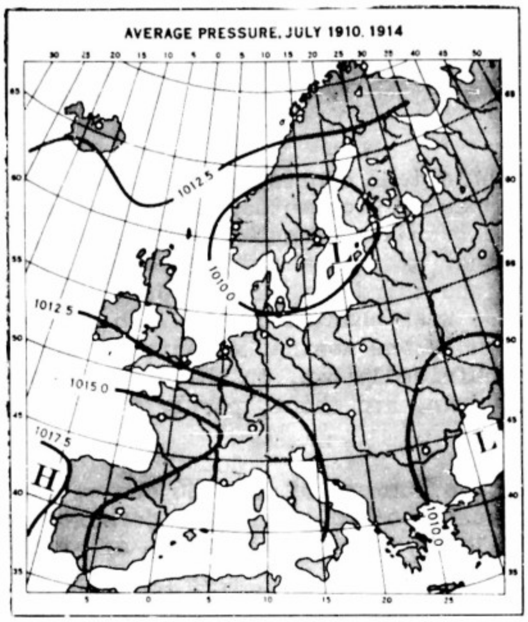


Fig. 13

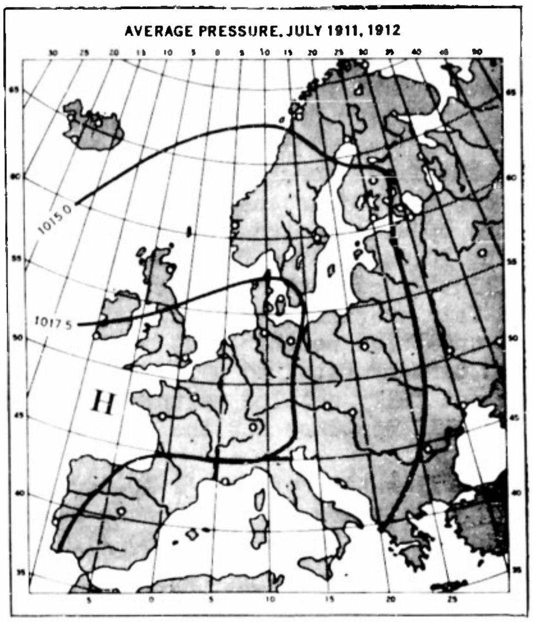


Fig. 14

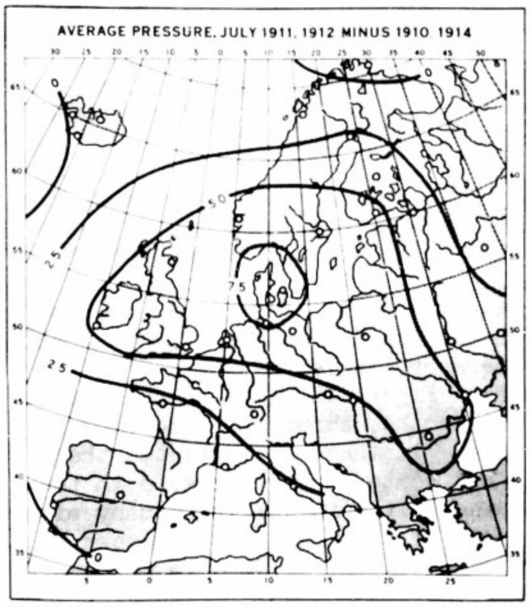


Fig. 15

Figure 13. Selected averaged maps of sea-level pressure associated with heavy precipitation in Germany in July. (Baur [8])

Figure 14. Selected averaged maps of sea-level pressure associated with extremely light precipitation in Germany during July. (Baur [8])

Figure 15. Chart showing the algebraic difference between the mean pressures in the dry and wet July months. (Baur [8])

In a similar fashion Baur derived a multiple regression equation for the relative temperature of the winter season in Germany as a function of the following five parameters: the temperature in Germany during the preceding February to June, the temperature in Norway from June to October, the temperature in west Greenland from July to August, the pressure difference between the Azores and Ireland from April to June, and the temperature in the eastern United States from September to November.

A final illustration of Baur's method is given in Figure 16 which indicates that a strengthened zonal circulation in Europe in February is followed by warm weather in Germany in March.

Baur's article in the Compendium [9] gives additional information on his method of preparing monthly and seasonal forecasts. It indicates that Baur, like Willett, has revised his earlier opinion of the importance of the sun on terrestrial weather. "The fluctuations in the solar radiation represent complexes of conditions that govern the course of the weather," he concludes. As evidence he cites impressive statistics on the relation between weather elements in widely scattered parts of the world and variations of the solar constant and sunspot numbers. These relations offer promise for future research, but they are not yet definite or conclusive enough to be used for the regular preparation of extended-period weather forecasts.

Baur [9] also has refined his statistical technique which he calls the "statistics of individual cases." The method is designed to account for the physical processes and the special characteristics of each particular case. This is accomplished by stratifying the data and selecting only those cases which fulfill certain extreme requirements. For example, Table 3 lists the years for the period from 1881-to 1948 during which the mean sea level pressure between 21 September and 30 September at Moscow was at least 2 mb above normal and, furthermore, the mean pressure departure was positive for Berlin from 21-30 September and for Moscow from 1-30 September. In every one of the 13 years during which these requirements were satisfied, the average temperature of the subsequent winter in central Europe was greater than 0.6°C above normal. In similar fashion it was found that abnormally warm winters in central Europe occurred in every case of the 13 years from 1884 to 1947 when the first half of December was more than 3°C above normal in central Europe. However, if the first half of December was below normal by just as many degrees, temperatures during the following midwinter were subnormal in only 4 out of 14 cases; in 10 cases, the midwinter was warmer than normal. It is thus apparent that this method can be applied only in a few selected cases; in the great majority of cases no forecast can be issued. Furthermore it prescribes a condition which is sufficient only; it implies nothing about necessary or causal conditions. Thus many warm winters in Europe were not preceded by warm temperature in December or high pressure in September. How can they be forecast? Finally, the method adds little or our understanding of the physical mechanism which is operating. For these reasons Baur [9] admits that "all demands for regular issues of monthly and seasonal forecasts must be declined in the present state of our knowledge."

B. North American Types.

In North America, the foremost exponents of weather-typing in extended-period forecasting are Krick [41] and Elliott [25]. They have classified many years of analyzed sea-level maps for the Pacific, North America, and North Atlantic regions. The eastern lobe of the semi-permanent Pacific sea-level anticyclone, the Aleutian low, the trajectory of polar outbreaks, and the direction of motion of migratory storm centers are used in the determination of these types. The

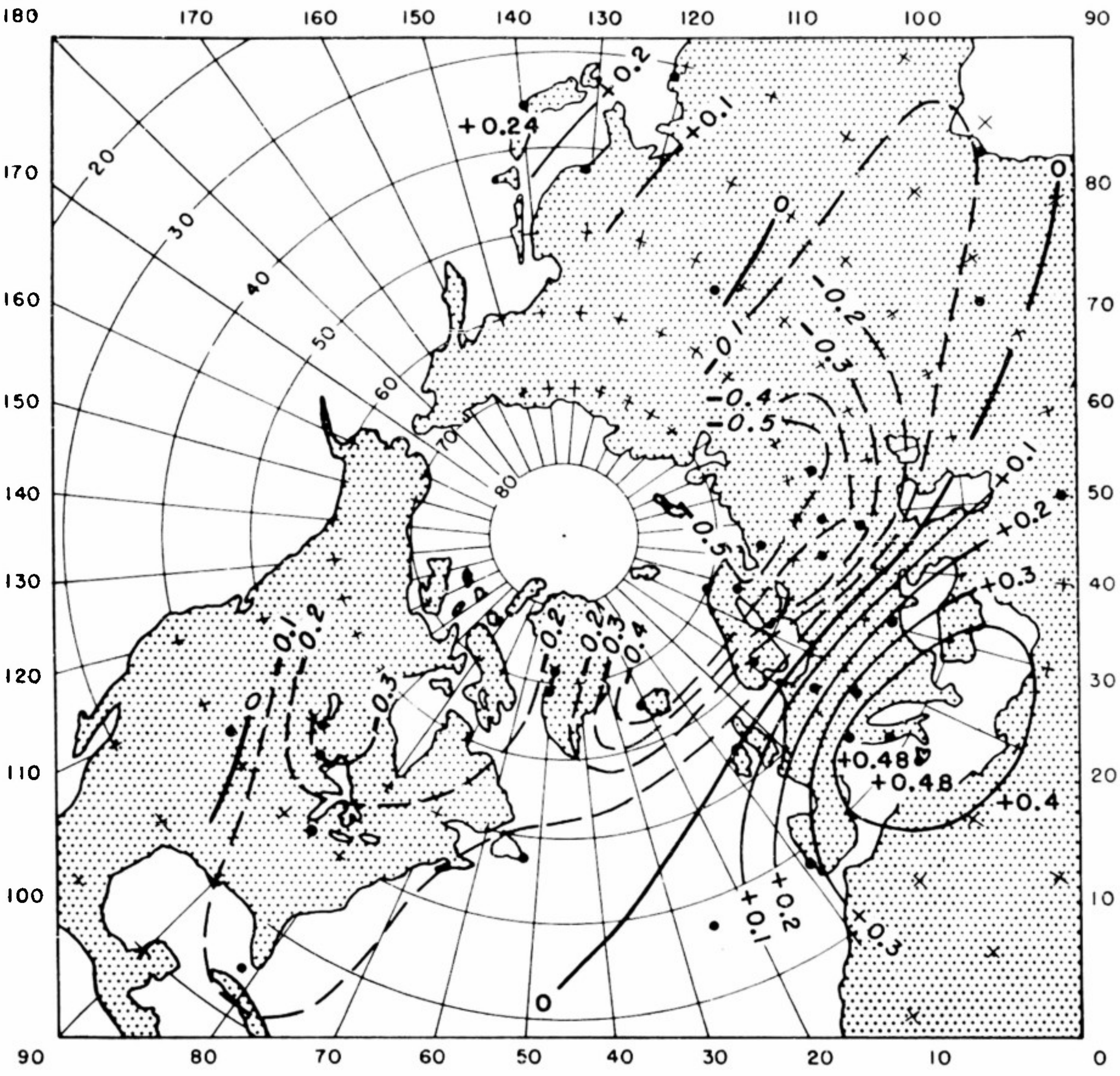


Figure 16. Correlation of March temperature in Germany with preceding February pressure (1874-1923). (Baur [8])

TABLE 3

Pressure Anomalies During the European "Altweibersommer" and Temperature Character of the Subsequent Winter.

Year	Pressure departure (in mb)			Temperature departure of the subsequent winter in central Europe (deg C)
	Sept. 21 to 30		Sept. 1 to 30	
	Moscow	Berlin	Moscow	
1884	+ 5.3	+ 3.7	+ 3.5	+ 0.9
1901	8.3	2.4	4.7	1.4
1902	2.3	9.3	0.9	0.7
1904	16.7	1.5	8.8	1.1
1909	5.6	2.0	5.5	2.2
1912	7.2	9.7	2.8	1.5
1913	4.8	6.0	1.3	0.8
1920	12.3	5.1	3.2	2.4
1926	4.3	1.1	0.1	1.6
1929	6.3	5.9	1.3	2.0
1937	3.7	2.3	0.9	1.2
1938	12.4	3.9	5.9	1.2
1947	+ 5.7	+ 0.4	+ 1.2	+ 2.2

illustrations and descriptive statements in this manual regarding these types have been taken from publications by these authors, primarily Elliott [26, 27].

The original types developed primarily at the California Institute of Technology were arranged so as to restrict the life history of a type to 6 ± 1 days. The first phase of most of these types is defined to begin when the first principal trough, a surface trough containing a single cyclone family, crosses 135°W longitude. Such troughs usually are located about three days apart, two of them composing the life history of a type. The first phase of a type is considered to move from west to east with the principal troughs. For example, by the time the first phase affects the Mississippi Valley the next principal trough, fourth phase, would be affecting the west coast.

Experience revealed that two of the most important shortcomings of this method (Elliott [27]) were the forcing of types into a somewhat arbitrary six-day life history and the disregarding of upper-air data in the original "type" classifications. Consequently, new typing methods have since been developed, using upper-air data when available. In these, the lifetime of a type corresponds to the passage of a single cyclone family, usually three days with considerable variation, across a region. It

was found that, for classification purposes, the weather of a region generally can be divided into two distinct classes according to flow patterns—meridional and zonal.

Meridional flow types are characterized by large-amplitude, upper-level, trough-ridge systems which steer migratory sea-level pressure centers abnormally far north or south of their average tracks. Polar outbreaks penetrating far to the south also are frequent with these types. Abnormally cold surface temperatures usually are found behind and in the areas between the trough and the next ridge system to the east. The areas of maximum cloudiness and precipitation are found immediately ahead of the upper-level trough.

Zonal flow types are characterized by relatively flat westerly flow. These types are classified according to the latitude of the westerly wind belt. Cold surface-temperature anomalies usually are found in the polar air north of the zonal wind belt with warm anomalies to the south. The heaviest precipitation is supposed to occur along the zone of greatest temperature contrasts.

In all the figures accompanying this section the schematic 700-mb flow for each type is indicated by dashed lines and arrows, areas of persistent high pressure are delineated by stippling, and the trajectories of major polar outbreaks are shown by double arrows. These schematic diagrams and the accompanying explanations pertain to "winter types."

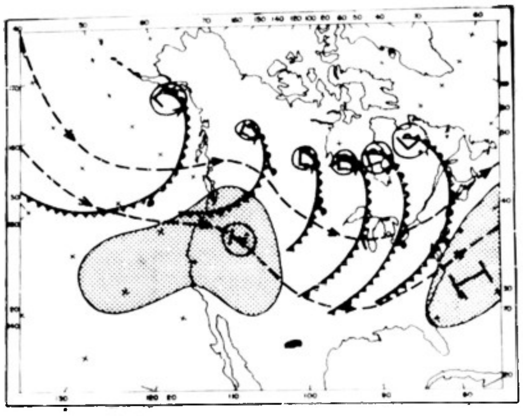
According to Elliott [26] "the same typing scheme applies equally well to other seasons except for minor seasonal variations. The seasonal differences in weather patterns are expressed primarily by different frequencies of occurrence of the various types. Thus, there are certain types which do not occur at all in summer, although all summer types do occur in slightly modified form in winter."

Meridional Types. Schematic diagrams representing the major features of the flow patterns occurring with a number of the more important wintertime meridional weather types of North America are shown in Figure 17. The position of each type in the column is determined by the degree to which it displays the characteristic of the category. The principal upper-level trough over North America usually becomes more intense as it shifts westward. The average positions of the upper-level crest and downstream trough for each type are shown in Table 4.

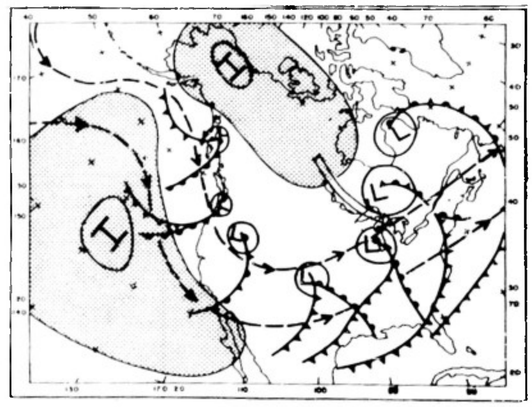
B_{n-a} and B_{n-b} have similar patterns with respect to the location of their upper-level ridges and troughs. The amplitude of these systems is the major difference between the types. Each has a strong persistent Great Basin sea-level anticyclone which diverts migratory storm centers moving eastward from the semi-permanent Gulf of Alaska low northward as they enter the North American continent. In B_{n-a} there is very little temperature contrast across the fronts. However, in the B_{n-b} type the low center, in accordance with the deeper upper-level trough, is steered more to the south as it enters central Canada. A strong cold front is generated along the mP-cP front in the prairie provinces. This is followed by cold continental polar outbreaks moving south-southeastward just east of the Rockies. As the cold air penetrates to far-southerly latitudes, frontal waves are frequently generated in the eastern Gulf of Mexico or along the east coast.

In B_{n-c} the longitudes of the upper-level trough-ridge systems are located approximately 10 to 15 degrees farther westward than those of the previous types,

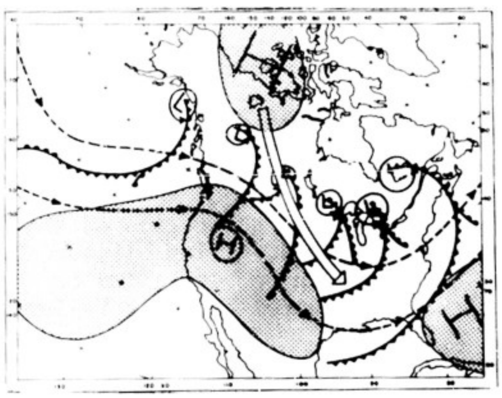
TYPE [illegible] OF NORTH AMERICAN WEATHER TYPES



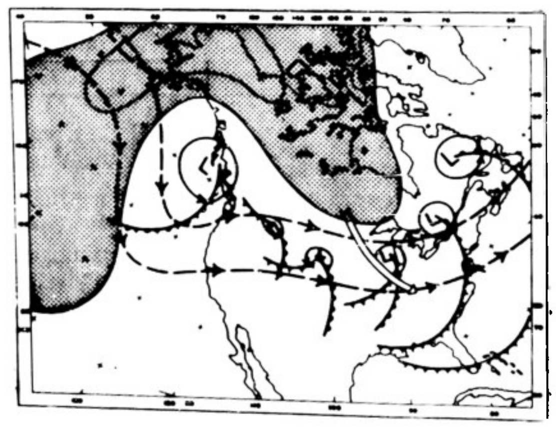
TYPE A OF NORTH AMERICAN WEATHER TYPES



TYPE Bn-b OF NORTH AMERICAN WEATHER TYPES



TYPE D OF NORTH AMERICAN WEATHER TYPES



TYPE Bn-c OF NORTH AMERICAN WEATHER TYPES

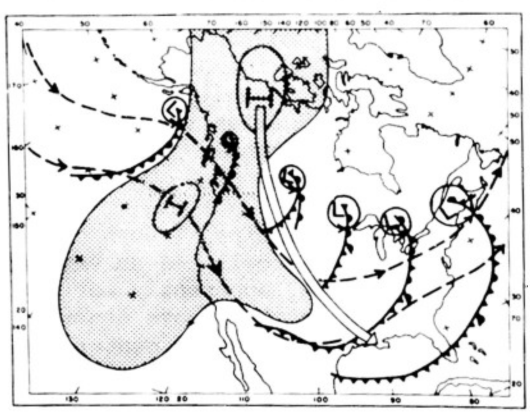


Figure 17. Schematic diagrams showing the more important winter-time meridional weather types for North America. (Elliott [26])

TABLE 4

Mean Positions of Crests and Troughs
for Various Meridional Flow Types

Meridional Flow Type	Western Crest Position	Eastern Trough Position
B_{n-a}	115° to 120° west	about 90° west
B_{n-b}	115° to 120° west	about 90° west
B_{n-c}	about 135° west	about 100° west
A	145° to 150° west	105° to 115° west
D	about 160° west	130° to 135° west
C_L	about 125° west	about 85° west
C_H	about 130° west	70° to 80° west

and the eastern trough is much deeper. The Great Basin sea-level anticyclone is considerably weaker and merges to the west with the Pacific anticyclone. The resulting high-pressure belt shelters the west coast of the United States from migratory storm centers which are now steered through British Columbia. As the centers enter central Canada they plunge southward and deepen in the region of the upper-level trough. Another major low center deepens in Colorado giving blizzard conditions to the eastern mountain areas. Cold cP air pours in on both sides of the divide. Heavy precipitation occurs throughout the Mississippi and Ohio Valley regions.

A further westward shift of the upper-level trough position is evident in Type A. The Basin anticyclone has vanished as a semi-permanent feature in favor of the unusually strong and far northerly displaced eastern lobe of the Pacific anticyclone. Surface waves which form along the southeast Alaskan or British Columbian Coast are steered rapidly down the coast through Washington and Oregon into the Great Basin Area. As the cyclones move eastward across the Rockies, further intensification occurs. The deepened centers then move northeastward across the Great Lakes and into Canada. Surface temperatures are abnormally cold west of the Rockies and abnormally warm throughout the central and eastern portions of the United States. Precipitation is heaviest in the Mississippi and Ohio Valleys.

Type D represents the extreme meridional type, with the principal trough off the West Coast. At the surface, the eastern lobe of the Pacific cell has an unusual "horseshoe-shape", extending from its normal position northward, apparently merging with the Alaskan cold polar-continental high. As the frontal systems move eastward from a semipermanent low center off the British Columbia coast, new wave centers develop in Montana and are steered eastward through central and northeastern United States. The principal outbreak of cold air occurs so far to the west that a minor cold outbreak is found to the rear of the secondary trough along the east coast of North America.

The meridional types, C_L and C_H, are characterized by an abnormally displaced

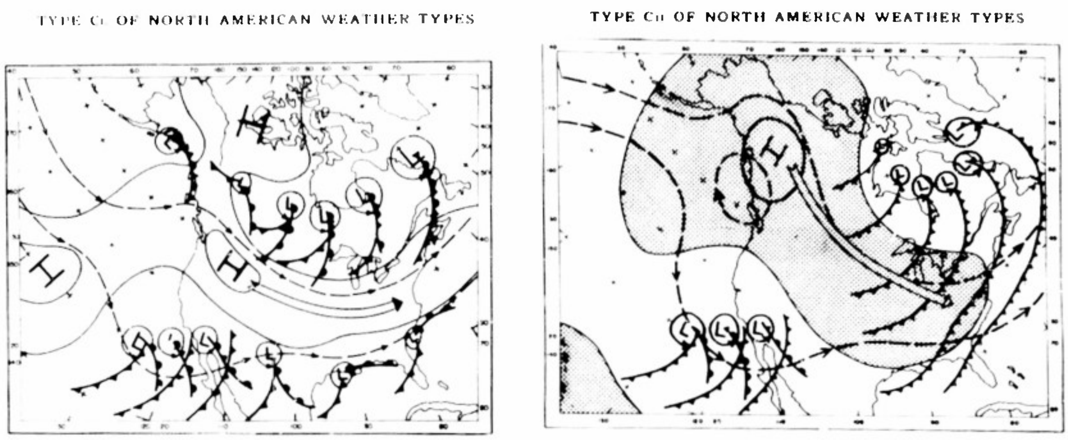


Figure 18. Schematic diagrams showing the wintertime meridional weather types for North America associated with an abnormally displaced sea-level high-pressure center in British Columbia. (Elliott [26])

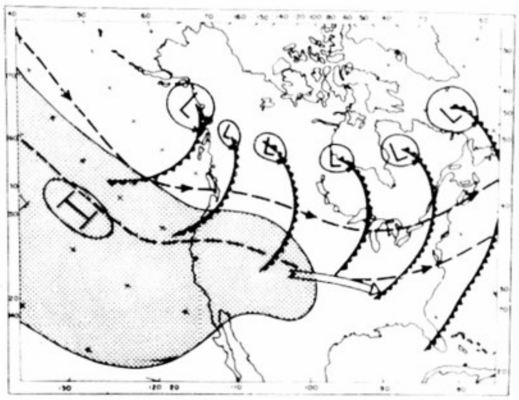
Great Basin High with the center in British Columbia, (Figure 18). This causes a split in the upper-level westerly wind belt resulting in two storm tracks over western North America. These branches later converge downstream. The northern branch moves along a crest at about 125°W and the southern branch moving along a trough at this same longitude.

Type C_L designates a persistent sea-level Basin high of moderate intensity and type C_H one of extreme intensity, 1040 mb or more, both centered far to the north in British Columbia as indicated by the double arrows. As these highs migrate eastward others immediately develop over the northern Great Basin to replace them.

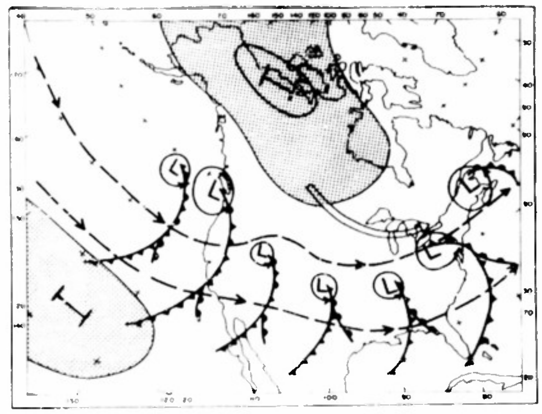
These types produce the heaviest known rainfall in southern California. Polar outbreaks, principally with C_H types, are most pronounced in the Great Plain states. As the storm centers move eastward along the southern path their motion is very erratic, and they often appear on the weather map as several closely-spaced waves.

Zonal Types. Some of the zonal flow types are shown in Figure 19. The position of each type in its column reflects the degree to which it displays the characteristics of the category. The strength of the zonal flow usually increases with a southward shift occurs over a sector 90° or (more) wide and is accompanied by the formation of extensive polar anticyclones to the north of the storm track. A measure of the southward shift of westerlies is the latitude at which the low center crosses the Rockies (105° West Longitude) (see Table 5).

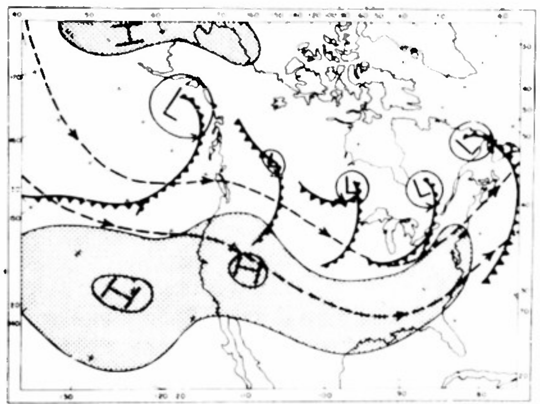
TYPE B OF NORTH AMERICAN WEATHER TYPES



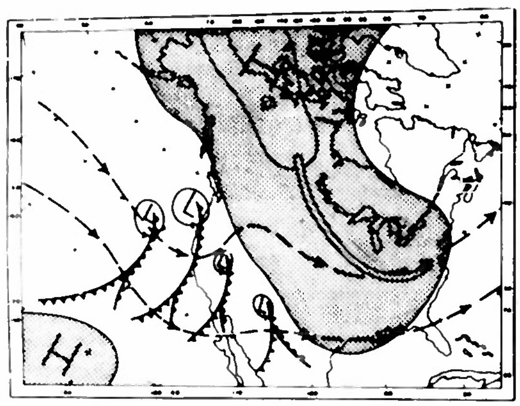
TYPE E_U OF NORTH AMERICAN WEATHER TYPES



TYPE B_S OF NORTH AMERICAN WEATHER TYPES



TYPE E_H OF NORTH AMERICAN WEATHER TYPES



TYPE E_L OF NORTH AMERICAN WEATHER TYPES

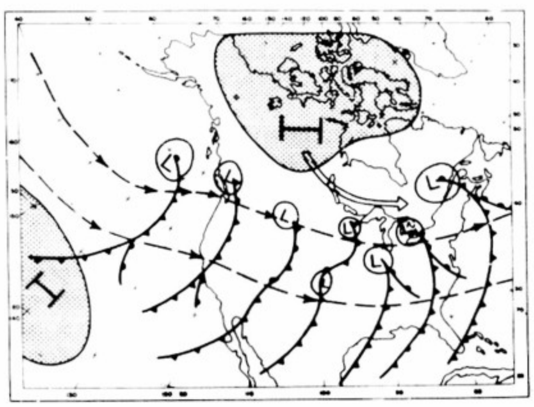


Figure 19. Schematic diagrams showing the more important winter-time zonal flow types for North America. (Elliott [26])

TABLE 5

Latitude of Low Center over Rockies with Zonal Flow Types

Zonal Flow Type	Latitude of Low Center Trajectory at 105°W
B	59° North
B_s	55° North
E_L	47° North
E_M	40° North
E_H	34° North

Type B is characterized by a northerly displaced storm track with a belt of well-developed subtropical anticyclones to the south. The upper-level flow is almost straight west to east except for minor troughs off each coast of the United States. The migratory storm centers which move eastward from the Gulf of Alaska through northern Canada have weak frontal systems which trail southward from the center into the United States. No strong polar outbreaks occur in the United States. with this type. Precipitation is light except in northwestern area of the United States and parts of the Gulf States. Modifications of this type are discussed under the meridional flow types.

Type B_s is quite similar to B_{n-a} of the meridional category except that the eastern upper level trough is deeper and the upper level western ridge is weaker. A small portion of the Gulf of Alaska low breaks off as a frontal system and moves eastward across the Rockies intensifying to the north of the Great Lakes. As the low moves rapidly eastward from the Rockies, chinook winds prevail from Cheyenne to Calgary. Another low often follows within two days. In southern California strong, dry, gusty, "Santa Ana" winds often develop causing considerable damage in the coastal regions.

Type E_L represents a more southerly displaced belt of upper-level westerlies than the previous types. A weak but persistent cold continental high stagnates in northern Canada and Alaska. Storm centers enter western North America near the 50th parallel and dip slightly southward as they cross the Rockies. A new wave often develops along the frontal zone just east of the Rockies. This becomes a major storm and then travels north-eastward across the eastern part of North America. At times when the air north of the storm track is exceptionally cold, the increased temperature gradient and wind field cause the low centers to move much more rapidly than indicated on the map. In fact, the movement is so rapid that waves do not have "time" to develop on the frontal system.

In type E_M the upper-level westerlies (over an area from the mid-Pacific to the U. S. Atlantic coast) are displaced considerably further south than normal and a large persistent sea-level high is located in Alaska and northwest Canada. Cyclones approaching the west coast reach their maximum intensity just off short at 45°N to

50°N. As the frontal zone moves, a new cyclonic center develops in the Great Basin. This storm moves east-southeastward, being continually pressed southward by the cold polar air to the north until it reaches the Appalachians where it deepens rapidly and begins to move northeastward. Precipitation is heavy along the west coast of the United States, especially northern California. A band of heavy precipitation also is experienced in a zone extending from the Gulf States along the Appalachians to New England. Most of the country is near or above normal in temperature with the exception of the Great Lakes and New England area.

Type E_H designates an extreme southward shift of the belt of upper level westerlies over a broad sector from mid-Pacific to the east coast, with an exceptionally strong surface high centered in Alaska and northwest Canada and extending southeastward over most of the North American continent. This high completely dominates the weather over the United States, forcing storms which enter the west coast at low latitudes to move southward around the southern periphery of the high. These storms usually weaken and disappear from the surface weather map before reaching the Gulf of Mexico. The only appreciable area of precipitation is found along the southern part of the west coast. Almost the entire country has abnormally clear and cold weather.

Gulf Types. As the western storms mentioned above move eastward, a trailing frontal remnant is often left in the Gulf of Mexico. When the frontal trough from a new cyclone enters this area cyclogenesis often occurs on the Gulf front. The newly formed Gulf wave then moves northeastward and dominates the weather in the eastern United States. Two such types are represented by G_a and G_b (Figure 20).

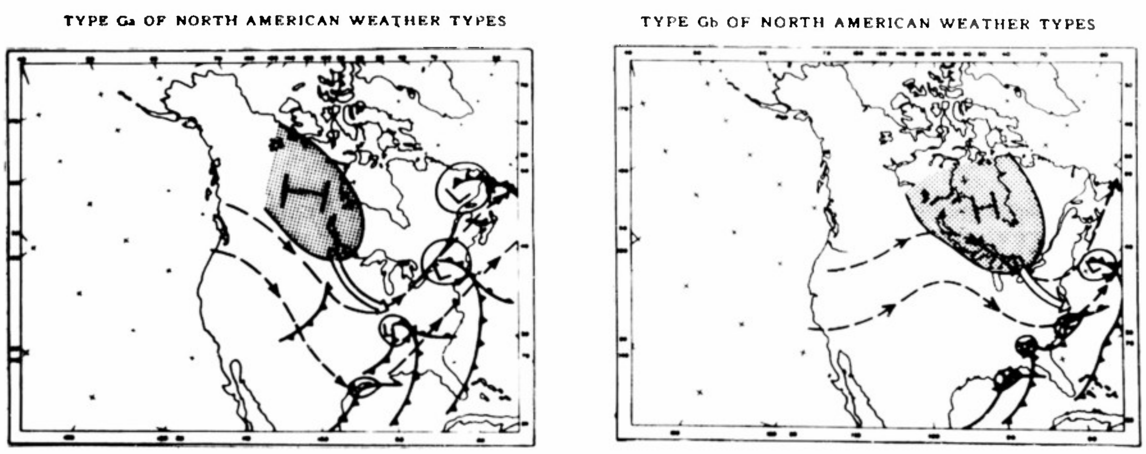


Figure 20. Schematic diagrams showing the wintertime types for the Gulf of Mexico. (Elliott [26])

Type G_a is characterized by an upper level-trough in central and eastern parts of the United States which steers the newly formed Gulf-wave northward and northeastward through the eastern U. S., producing heavy precipitation throughout this area. These waves often recur and frequently follow the meridional types with upper-level ridge between 110°W and 130°W. This includes all the B-north types.

Type G_b has an associated upper level-ridge over the central United States and a trough off the east coast. Waves are formed on the stationary front in the Gulf of Mexico in conjunction with the frontal trough of the preceding type. These waves then move east-northeastward entering the country east of New Orleans. A new low center forms off the Carolina coast when the old center reaches the southern Appalachians. This "Hatteras low" immediately becomes the prodominant storm and deepens rapidly as it progresses up the East coast, giving heavy precipitation throughout the coast area. This type of activity accounts for most of the snow storms from Washington, D. C., southward along the eastern Coastal plains. Its effect on more northern coastal stations depends on the proximity of the Atlantic storm center to the coast. Cold polar outbreaks occur primarily in eastern United States. This type quite frequently follows an A or D type in the western zone.

Hudson Bay Types. H_a and H_b are identified by a strong Hudson Bay surface high (see Figure 21). If this high is of polar origin and extends southward in the form of a ridge with a separate high center over the Great Lakes, it is known as type H_a. The high-pressure area is quite persistent, causing low centers which enter western United States to be deflected southward. The resultant movements of these storms are very erratic. This type is usually found in conjunction with E types of the western sector. Showery type precipitation is very frequent in the frontal zone.

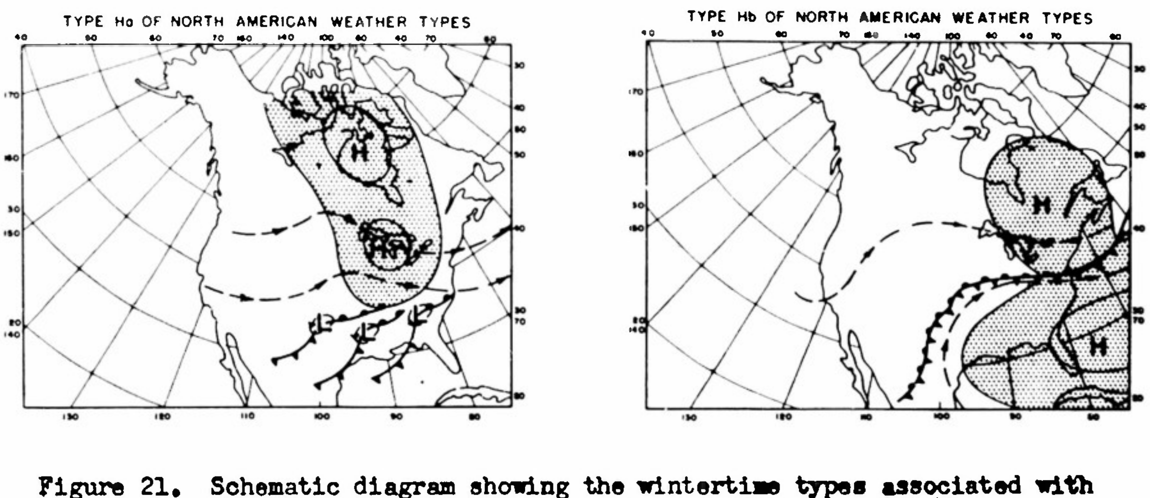


Figure 21. Schematic diagram showing the wintertime types associated with high sea-level pressure in the Hudson Bay area. (Elliott [26])

Type H_b is associated with a strong tropical sea-level high pressure cell over southeastern United States which completely dominates the circulation, causing hot humid conditions throughout the entire area. Another sea-level high-pressure cell of polar origin with cool and relatively dry air at the surface is found over Quebec and Hudson Bay. A nearly east-west frontal zone separates these two semi-permanent high pressure cells. Slight variations in these cells as they battle for domination over eastern United States cause considerable variation in temperatures at stations located in the frontal zone. Thunderstorms are frequent along this front. This type occurs almost exclusively in summer.

IV. ANALOGUE METHODS

Numerous attempts have been made to use analogues for extended-period forecasting [8, 41, 65, 79, 81]. This technique received particular consideration by Air Weather Service personnel during and shortly after World War II. It is generally recognized that certain analogues could be very useful in extended-period forecasting; but as yet no satisfactory method has been devised to select them.

The basic theory underlying the analogue technique is simple. If two identical weather situations are found, their subsequent evolutions also will be identical. If the proper analogue is found in the file of historical weather maps, a forecast for a given period can be made by reading the weather directly from the subsequent series of observed maps.

The analogue method would be a rapid, inexpensive, and objective way of issuing a forecast without the necessity of relying upon complex and poorly perfected methods involving subtle dynamical or physical reasoning. Likewise, it would not be necessary to consider climatological or orographical details since these are automatically included in the various analogues.

Unfortunately, however, it is almost impossible to find two maps which are identical. Furthermore, Darling [24] showed by exhaustive statistical tests that persistence is the principal factor taken into account when forecasts are made from analogous maps which have been selected without regard to their historical development.

Therefore it appears desirable to select analogues which have similar histories and which show marked agreement over large areas of the hemisphere at all levels of the atmosphere. Obviously, such a refinement greatly complicates the selection of an analogue. In the first place, since upper-air data are available for only a relatively short period of years, the number of historical maps available for analogue selection becomes quite limited. As further restrictions are established pertaining to agreement between sequences of maps, the number of good analogues diminishes even more rapidly.

Numerous statistical studies were conducted by Wadsworth [81] in evaluating and devising techniques for the mechanical selection of analogues. Tests were made to determine the tolerance which can be allowed in selecting an analogue. How closely must a past situation resemble the current situation for it to be considered a useful analogue for predicting future weather? Since it seems logical that maps with good correlation between them should have had fair agreement for at least three days in the past, tests were made to see if maps with a sequence of more than three

days and with a correlation in excess of 0.38 would prove better analogues. The results of this study are discouraging since Wadsworth states that "only 35 percent of the best analogues from each period showed a greater number of high correlations previous to the forecast period than the average of all analogues chosen on the basis of three correlations alone." However, it is quite possible that the correlation procedure is too refined in this instance since nearly all the subjective methods of picking analogues which are currently being used in meteorology do consider the sequence of maps prior to the analogue in making their selection. A statistical study of the results of analogue selections made by USAF during 1945-46 also showed the limitations of objective selection methods [99].

As yet there has been developed for extended-period forecasting no method of selecting analogues the success of which is not highly dependent on the judgment and experience of the forecaster. Such forecasting by modifying the analogue in accordance with its "small differences" from the current map, demands, in essence, that two forecasts be made. First, one must forecast where the analogue will be wrong; and then one must forecast how to change it. This often is more difficult than making the entire forecast by other techniques.

One of the most dangerous consequences of forecasting by analogues is the tendency to use them blindly without an adequate consideration of the underlying physical processes. The result is a detailed forecast in time and space beyond the warranted skill of the method.

Nevertheless, analogues should be more thoroughly investigated for usage in conjunction with other methods, either as an aid or a check on the pressure-pattern prognosis. Analogues might be selected on the basis of prognostic maps made by other methods, and then used in interpreting weather elements, frontal activity, air mass movements, and the like from these prognostic charts. In present day forecasting, trends within a forecast period are often much more difficult to interpret than many forecasters realize and yet, in the final analysis, they are frequently the most desired portion of the extended-period forecast.

A. Various Methods of Selecting Analogues.

A punch card analogue file has been completed by Air Weather Service for 40 years of sea-level maps (January 1899 through June 1939). The maps have been broken down into six overlapping major divisions: Atlantic, East Atlantic, Northwest (continental), Pacific Asia, and West Asia. Each of these divisions has been further divided into 73 zones.

During World War II analogues were selected daily by machine methods and distributed to Air Force weather stations. In making the selection the forecaster in Washington placed a transparent template over the analyzed map and noted the locations and intensities of the major pressure cells. This information was transmitted to the Data Control Unit where analogues were selected by IBM equipment. Ordinarily all the cards during each year of the 40 years of data for the preceding month and the month after the current date were used in this selection. In practice, the forecasters picked the "best" analogue by visual inspection from the group of machine-selected analogues.

Often, a great number of the machine-selected maps bore little resemblance to the current map because too much leeway was allowed in coding the locations and values of the pressure centers. In addition, consideration was not given to the

past history of analogues or their upper-air flow patterns. It has therefore been discontinued until current research reveals a better method of analogue selection.

Another method of selection has been used at Bad Kissingen, Germany [29, 102]. Tiny pictures of European maps, about one inch square, are mounted on large cards for each month. Each card contains several hundred maps representing many years of data. Analogues for current or prognostic maps are found by a visual inspection of these tiny pictures. Such a pictorial presentation affords a rapid means of considering similarity of patterns, historical development, and prognostic evolution in the determination of analogous situations.

In France, Donzel uses a subjective method of visually selecting analogues which is based on the large-scale features of the circulation (Namias [56]). He attempts to classify the "best analogues" and varies the usage of analogues according to the following classes:

Case 1. Simple analogue (rare)

(a) Same season, (b) same centers of action, (c) same shape of centers of action, (d) similar evolution; these result in same immediate future evolution, and are valid for same period in the future that evolution has been similar in the past.

Case 2. Composite analogy.

Must meet (a), (b), (c) under case 1. Several analogues should be considered to draw conclusions regarding large-scale weather connections but detailed weather forecasts are not warranted.

Case 3. Partial analogy.

Must meet (a) and (b) under case 1. These analogues are used primarily in selecting weather types.

Somewhat similar techniques for using analogues are described by L. A. Vital [80]. He suggests the construction of composite or averaged maps of all the best analogues to obtain those features inherent in all of them. These features, common to all the analogues, would reflect the most important characteristics of the large-scale weather processes and serve as the basis for forecasts. Elements of separate analogues would stand out sharply when compared to the averaged maps and these deviations could serve as a means of modifying the analogue forecast.

A rather novel method of cataloguing historical weather maps was introduced during 1940-1945 by E. Grytøyr [79]. Although this method was developed primarily for short-period weather forecasting at Oslo, it is quite conceivable that such a technique, perhaps with modifications for larger areas and different localities, could be adapted to longer-period forecasting.

Grytøyr portrays many elements of a weather sequence on a chart, called a "clue diagram", by taking into detailed account the dynamic development of the weather processes in a rather small geographical area. The movements of air masses, fronts, and pressure systems for a series of maps are charted in an ingenious manner in accordance with their positions relative to Oslo. These diagrams are used in the visual selection of analogues.

B. The Pagava-Multanowski Technique.

Pagava's method [59] essentially is an extension of the empirical ideas of Multanowski [5, 6, 46-49, 71]. The basic notion of Multanowski's method is that arctic and polar air mass "injections" into temperate latitudes have a certain period or rhythm which can be used in forecasting [71]. Pagava's method is based in part on this allegedly "natural rhythmic" sequence of a cold anticyclonic system in the form of a "crest" (ridge) or closed cell of high pressure which moves along a north-south or northeast-southwest track through Europe and interrupts the normal west-to-east wind flow. This "diagnostic ultrapolar" rhythm is used by Pagava as a means of selecting analogues for extended-period forecasting. Each diagnostic-ultrapolar situation is examined for past or future rhythms of 90 ± 2 and 150 ± 2 days.

It is claimed that if an analogous situation can be found 90 ± 2 days before the date of the diagnostic ultrapolar situation no analogous synoptic situation will occur 90 ± 2 days in the future. However, if no analogous situation occurs 90 ± 2 days before the date of the diagnostic ultrapolar situation one will be found 90 ± 2 days in the future. The same considerations hold for the 150 ± 2 day rhythm which apparently is independent of the 90-day cycle. Thus from each diagnostic ultrapolar situation one 90 ± 2 day and one 150 ± 2 day analogue will be found. Both may be in the past, both in the future, or one in the past and one in the future. Forecasts for extended periods of time can be issued directly from the sequence of these analogues.

In practice these basic rules are supplemented in various ways. For example, one method treats the midpoint of the rhythm period, i.e., 45 ± 2 and 75 ± 2 days in both past and future, measured from the time of the diagnostic ultrapolar situation, while others deal with different phases of development of the synoptic process.

During the last war Pagava visited this country and Air Force meteorologists discussed his ideas with him. Some of the Pagava-Multanowski concepts and experiences were found helpful in guiding the Air Force experiments in extended forecasting. The Pagava "technique" as such was not considered promising because of the lack of a convincing basis, there being no rigorous proof of the reality of the Multanowski rhythms. The Pagava method as described in his book (translated by USAF) [59] and in later papers by his associates is so involved and presumptious that it is extremely difficult to grasp clearly the characteristics which could justify the claims made for its success in the USSR. It is believed that its success in Russia may be due to the general synoptic experience of the forecasters and in spite of the very dubious "natural rhythm" theory of Multanowski. After extensive statistical analysis, Wadsworth [81] was unable to find any such rhythms in weather patterns. The nature of the circulation over USSR with its predominance of anticyclonic patterns, perhaps gives Multanowski's scheme a greater validity there than in North America. The AWS Forecast Center at Rhein-Main has made some use of the Multanowski-Pagava "laws" in selecting analogues for medium-range (extended) forecasts; here again the utility results from long experience and the combination of the technique with other methods [102]. It is to be noted, moreover, that Pagava's technique makes extensiv use of historical weather maps and his forecasting may thus empirically embody all the validity that any analogue method can have.

V. COMBINED PHYSICAL-EMPIRICAL METHODS

A. Mitchell's Method.

This method of preparing seven-day forecasts was introduced in 1944 by C. L. Mitchell, retired, of the U. S. Weather Bureau [4, 28]. It assumes that waves in the westerlies have a period of six days and that tropical air masses which become quasi-stagnant at high latitudes exercise a profound effect on the general circulation over a very large area for many days. The fundamental forecast tools are applied to the sea-level and 500-mb charts with particular emphasis on the motion of isallobaric centers at both these levels.

Upon the completion of the daily 0300Z northern hemisphere 500-mb analysis, an auxiliary, dependent chart was constructed. Three elements were displayed on this chart: (1) the 500-mb height anomaly at each point of a latitude-longitude network and isopleths of the height departure from normal, (2) the 24-hour 500-mb height change at each point of the network; (24-hour temperature changes also for reporting stations), and (3) tracks of isallobaric highs and lows for each day during the week. A modified version of this chart is shown in Figure 22. An estimate of the appearance of this chart one week in advance formed the basis of the extended-period forecast. The current 500-mb isallobaric centers were used to fix the positions of the seven-day prognostic isallobaric centers, which in turn were used to determine the location of above and below normal 500-mb heights. For example, an area of below normal heights is usually found about five degrees west of a katallobaric center, and an area of above normal heights as much as 15 to 20 degrees west of the corresponding anallobaric center. The prognostic positions of the isallobaric centers were also used to locate sea-level centers. Therefore the value of this method of extended-period forecasting depended primarily upon the accuracy with which 500-mb isallobaric centers and the related height-anomaly areas could be forecast. The principles for forecasting these phenomena can be broken down into two categories: (1) forecasting the longitude, and (2) forecasting the latitude of isallobaric centers. A discussion of these generalized principles will follow.

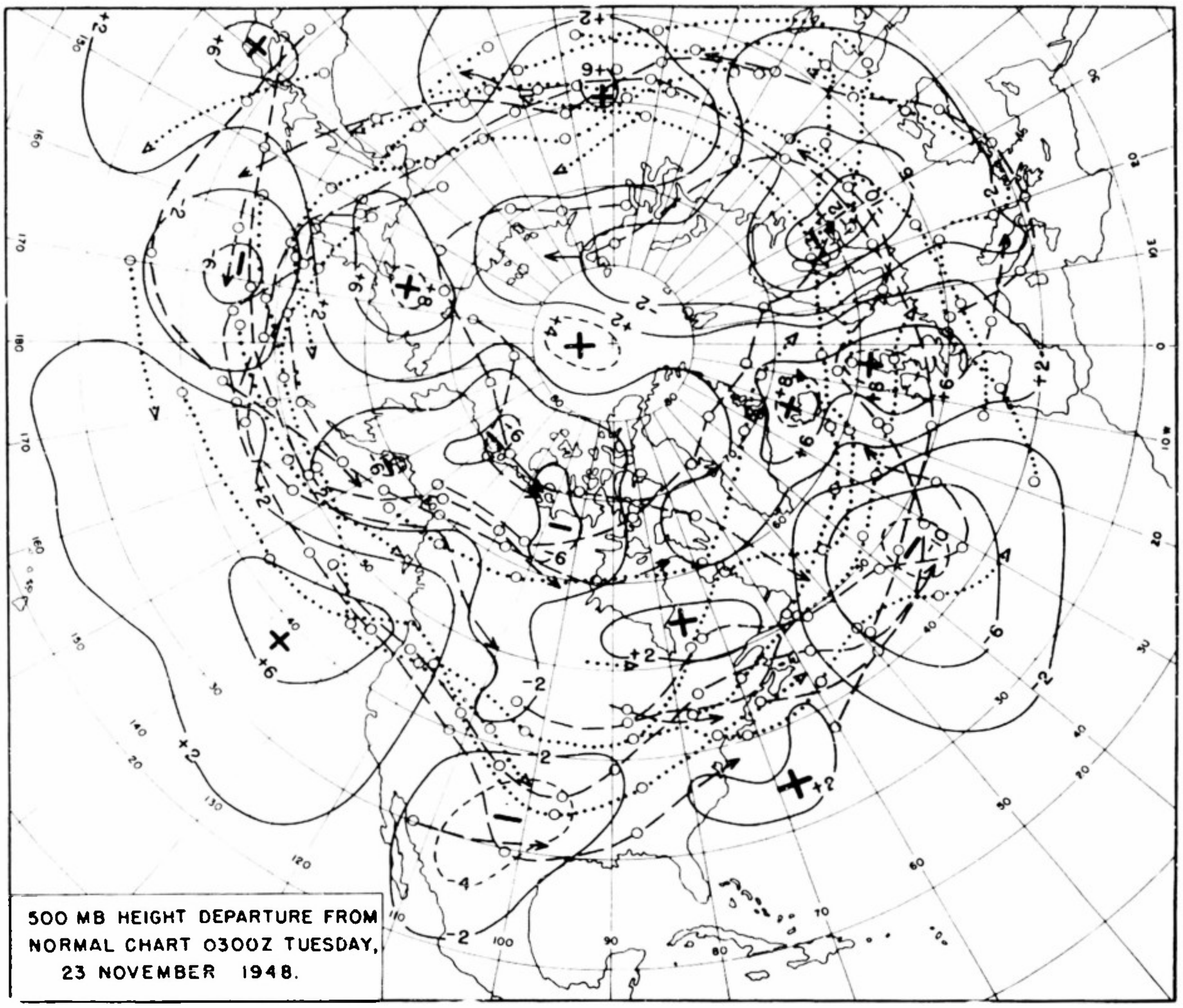
1. Rules for forecasting the longitude of height anomaly and isallobaric centers on the seven-day prognostic 500-mb chart:

a. If an isallobaric center is located in the belt of westerlies today, another isallobaric center of the same sign will be located 10 to 15 degrees (one day's motion) east of the current center seven days later.

b. Large above-normal height areas situated at or above 50°N and isolated from the subtropical source regions will usually persist for the seven-day period. These above-normal areas may be reduced and intensified by successive passages of katallobaric and anallobaric centers, but the original core should remain intact.

c. A large above-normal area in high latitudes usually is associated with a below-normal area in southern latitudes located about 20 degrees of longitude to the east of the current center of the above-normal area.

d. If a large above-normal area is situated below 55°N and is moving northeast (as evidenced by the 24-hour height change) a corresponding center will be located 15 to 20 degrees to the east and 5 to 10 degrees to the north of the current



500 MB HEIGHT DEPARTURE FROM NORMAL CHART 0300Z TUESDAY, 23 NOVEMBER 1948.

Figure 22. Typical 500-mb height anomaly chart with tracks of daily 5-mb isallobaric maxima and minima. (Fawcett [28]) Dashed lines indicate movement of 500-mb kotallobaric centers; dotted lines indicate movement of 500-mb anallobaric centers. Distance between circles indicate one day's movement while arrow indicates map-time position. (Alternate lines of height departure have been left out of figure for clarity.)

center in seven days.

Rule "a" shows that for strong westerly flow (high index) considerable reliance is placed on the occurrence of a six-day wave cycle. This cycle and the more common three-day wave cycle also are inherent in the North American typing method of the California Institute of Technology. Rules "b", "c", and "d" apply principally to meridional circulation patterns often characterized by blocking, low index, and short wave lengths. Much of the work of Namias and Elliott on blocking tends to substantiate these empirical rules by showing that blocking waves at high latitudes are persistent, slow moving, and associated with cold lows to the south and east.

2. Rules for forecasting the latitude of height anomaly and isallobaric centers on the seven-day prognostic 500-mb chart.

a. With zonal flow, anomaly centers currently located south of 50°N will be located nearer this latitude in seven days. Centers already located at 50°N will remain at that latitude.

b. Meridional circulation patterns with high or rising heights to the east and low or falling heights to the west of a center on the current day have an associated center at the same latitude, or farther north, seven days later. (See Figure 23.) Conversely, high or rising heights to the west of a center with low or falling heights to the east have a more southerly associated center seven days later.

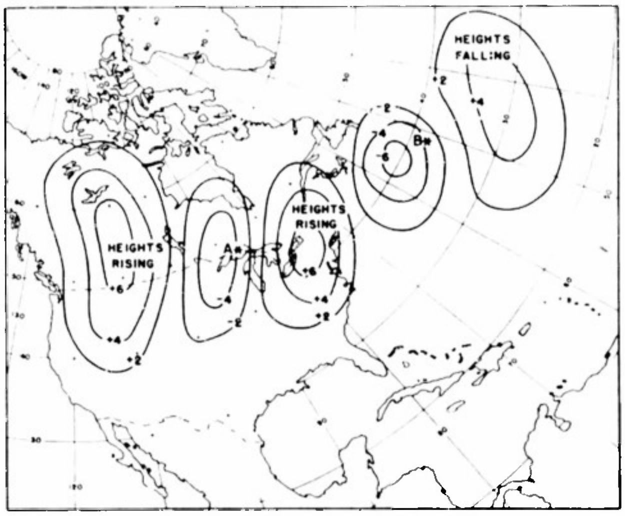


Figure 23. Idealized situation showing Mitchell's rules for forecasting the latitude of the height anomaly centers seven days in advance. Center at "A" will move northward, while center at "B" will move southward. (Fawcett [28])

Mitchell's empirical rules for forecasting the longitude and latitude of the height anomaly and isallobaric centers are consistent with meteorological theory and reasonably straightforward. In practice they were supplemented by an independent technique of forecasting the seven-day movement of the katallobaric centers from the current 500-mb height-departure chart. This appears to be the weakest link in the

entire technique since it primarily consisted of a day-to-day extrapolation of change centers seven days in advance. It has previously been pointed out that "short period" extrapolation techniques lose their effectiveness after approximately 48 hours. Furthermore, research on observed maps showed that 28 percent of the katallobaric centers were nonexistent after seven days. Such findings, added to the necessity for dealing with merging and splitting centers, make this portion of Mitchell's technique most unwieldy. The fact that he so often was successful in extrapolating migratory change centers for such an extended period is a tribute, in part, to his outstanding ability as a synoptician obtained through years of practical experience.

Following the location of a departure from normal area on the seven-day prognostic chart, a forecast of the intensity of the center was made. The intensity could not be prognosticated as accurately as the position of the surface centers. An absolute 500-mb height chart was obtained from the 500-mb height-anomaly chart simply by the addition of normal 500-mb values at each of the network of points. Such seven-day prognostic charts were prepared daily. Prognostic sea-level centers were located on the 500-mb prognostic height chart in the following manner: Centers of highs and lows were placed to the east of the 500-mb troughs and ridges in the areas of greatest 500-mb cyclonic and anticyclonic curvatures (Figure 24). The intensities of these prognostic sea-level centers were functions of the geography, season and normal intensities as well as any abnormal trend of the particular year.

In the preparation of the series of daily prognostic sea-level maps (Figure 25) the first day's prognosis was constructed using standard short-period methods. The positions of the sea-level centers for the past three or four prognostic charts were located from the daily seven-day prognostic 500-mb charts. The second and third day of the series represented a transition from the 24-hour prognostic centers using short range techniques to the seven-day prognostic centers using extended-period techniques. Making such a transition is one of the most difficult tasks in extended period forecasting. It was accomplished by establishing 48-hour and 72-hour prognostic positions of surface centers by short-period techniques, and adjusting the positions of the centers obtained by the extended- and short-period methods to reach agreement for this second and third day. No adjustment, however, was made beyond this length of time. Prognostic isobars and frontal structures were constructed and later used in the preparation of temperature and precipitation anomalies. This, too, was largely a subjective procedure with temperature forecasts primarily dependent on the prognosticated air masses and precipitation on the prognostic storm tracks.

In conclusion, the prognostic 500-mb chart and its derivatives were basic to Mitchell's technique. The prognostic sea-level chart and anomalies of precipitation and temperature are derived from them. Numerous tests and a running verification by the statistical division of the U. S. Weather Bureau have proven that these forecasts have some validity. However, much subjective reasoning and experience is required to complete a forecast using the method. This has been considered a major drawback to the system since a considerable apprenticeship under Mitchell's supervision was necessary before one could competently use the system of forecasting.

B. Mean Circulation Method.

The mean circulation method of extended-period forecasting seeks by physical reasoning and statistical procedures to forecast features of the atmospheric circulation which are represented by pressure patterns at one or more levels. It is of special importance because this method is used by the Extended Forecast Section of

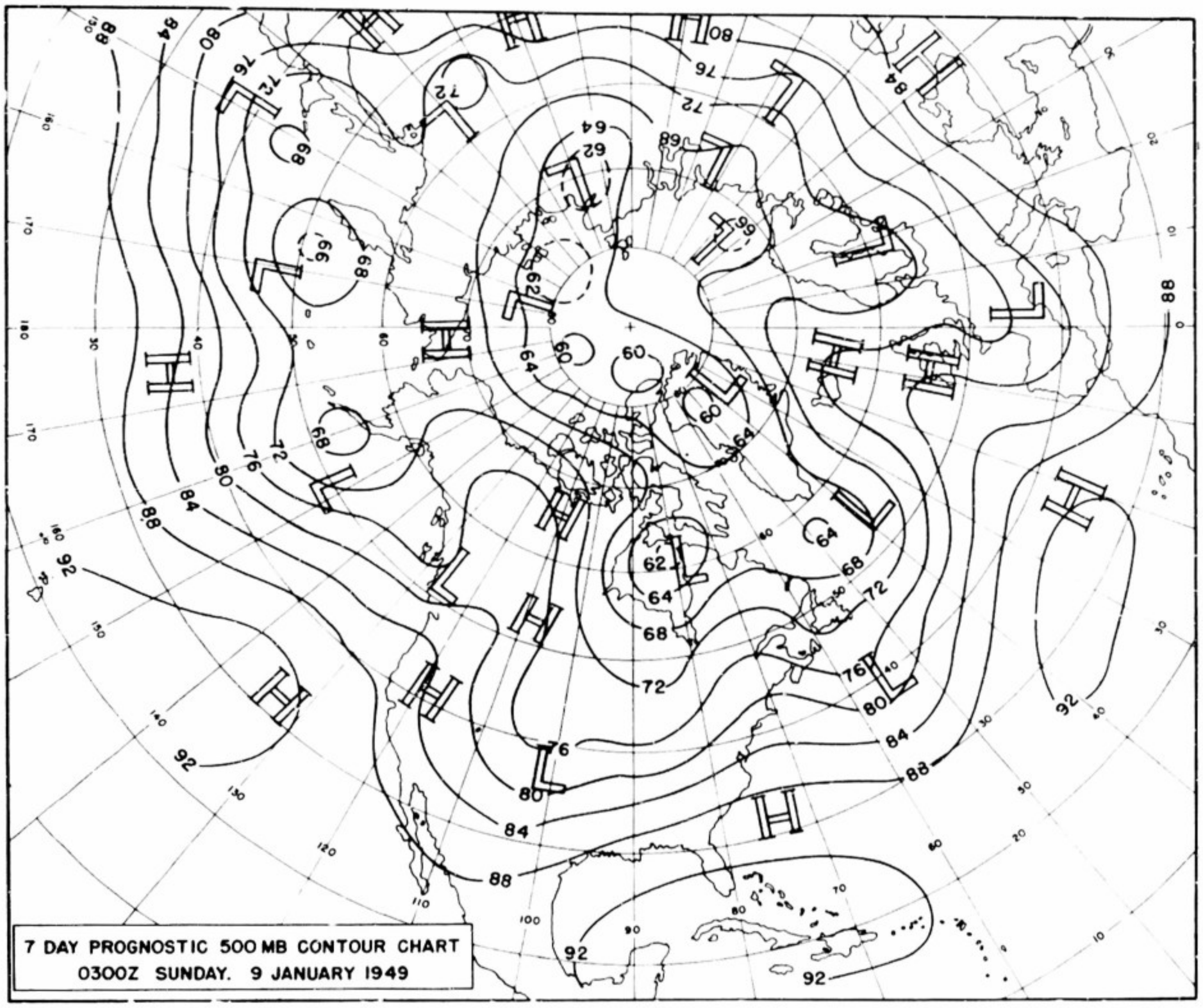


Figure 24. Chart showing positions of sea-level pressure centers relative to the contemporary 500-mb contours. (Fawcett [28]) H's and L's indicate prognostic positions of sea-level pressure centers at 1230Z, 9 January 1949. (Alternate contour lines on original maps have been omitted. Lines showing departure of height from normal also have been omitted.)

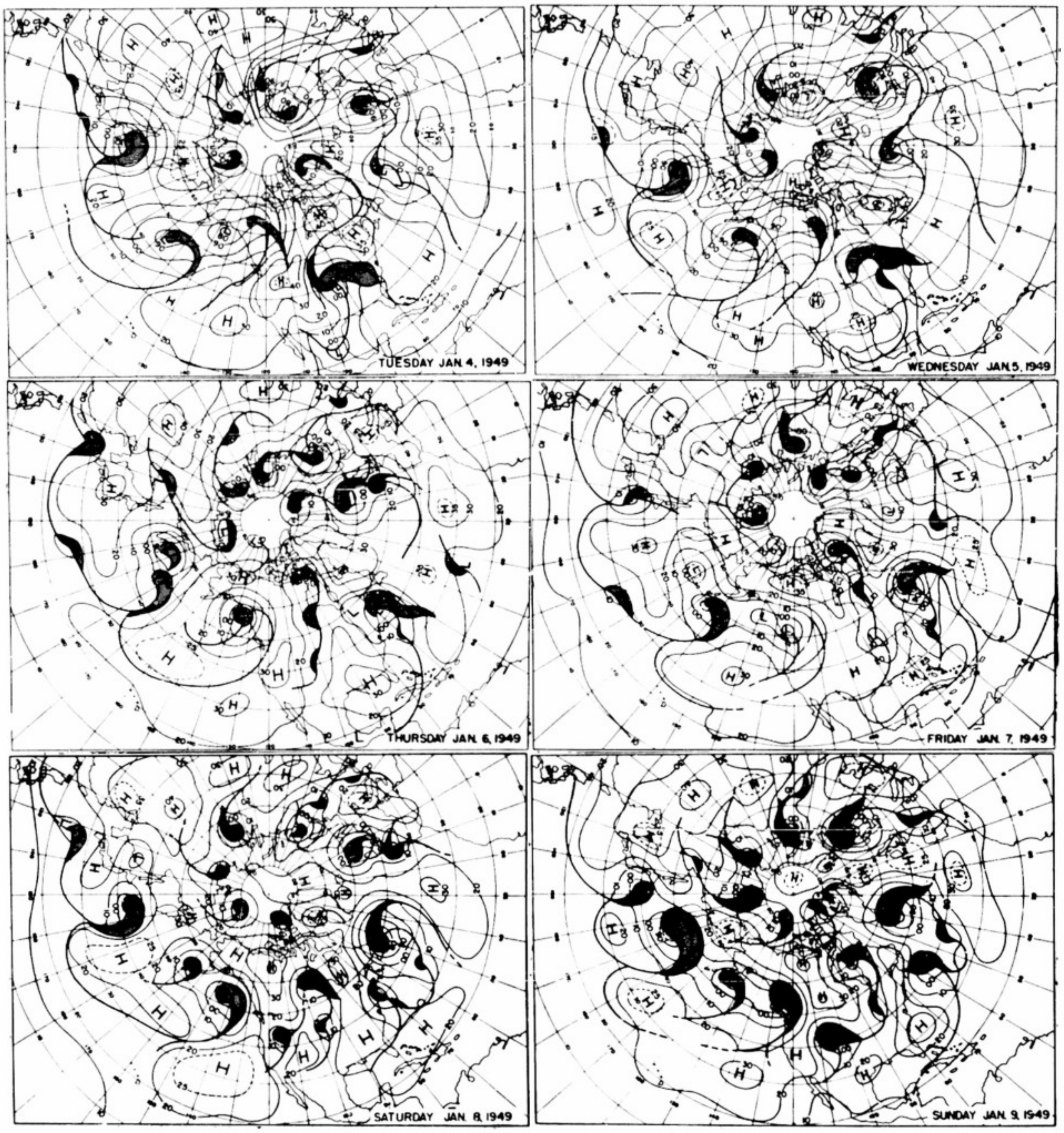


Figure 25. Series of six prognostic daily maps [28]. (Alternate isobars and air mass designations on original maps have been omitted.)

the U. S. Weather Bureau in preparing its forecasts which are disseminated by the Air Weather Service. This chapter will discuss the preparation of extended-period forecasts by the U. S. Weather Bureau and is based primarily on papers by Namias [53, 54] and on allied publications of the Weather Bureau's Extended Forecast Section.

There are four steps in the preparation of these forecasts: (a) Assessing the initial state of the general circulation; (b) Predicting the mean circulation for the five-day period ending six days in advance; (c) Interpreting the prognostic flow pattern in terms of the average weather expected during the period; and (d) Forecasting the trend and sequence of events within the period.

1. Assessing the Initial State of the Circulation. In the identification of the current state of the atmospheric circulation, as well as for the extended-period forecast, five-day averages are employed to mask out the minor fluctuations which Charney [20] has referred to as "meteorological noise." Sea-level, five-day means are obtained, for example, by averaging 10 twice-daily values of pressure at standard intersections of latitude and longitude on synoptic sea-level weather maps.

It is important for the following discussion to understand the concept and usage of mean charts. Through the mechanics of the averaging process it follows that a low-pressure center in a given area on a mean-pressure chart can result only from (a) a high frequency of lows in that area on the individual charts that have entered the averaging; or(b) from greater intensity of lows in that area compared to the surroundings; or (c) a combination of (a) and (b). Shorter-term mean charts are completely analogous to the normal chart in make-up and meaning. For any stated period, five days for instance, mean maps can be constructed to reveal the average conditions during that period.

Mean charts are employed by the extended-period forecaster to obtain a perspective of the large-scale features of the circulation which determine extended-period weather phenomena. The averaging process subordinates the minor, short-term processes which, though extremely important to the short-period forecaster as he considers the instantaneous state of meteorological affairs, may contribute little to the broad-scale developments.

The exact choice of period length is arbitrary. The period should be sufficiently long to exclude the small irregularities of daily synoptic charts yet it must be short-enough so that it does not obscure the trends of development the forecaster is seeking. Depending on the situation, one period may be more effective than another.

For an operational routine it is desirable to adhere to a standard period. Five days is one satisfactory period length; it offers convenience in the numerical averaging processes, since it consists of ten twice-daily values.

The 700-mb chart is used as the primary tool by the Extended Forecast Section. This level was selected since (a) it is removed from most surface frictional effects, (b) it is representative of conditions throughout the lower atmosphere, (c) data are plentiful, and (d) patterns at this level are relatively simple and easy to handle. Considerable attention has been given to research in forecasting the fundamental troughs and ridges at this level.

A schematic diagram of the normal middle-latitude wind fields at the surface and aloft (see Figure 26) reveals the existence of the well-known prevailing

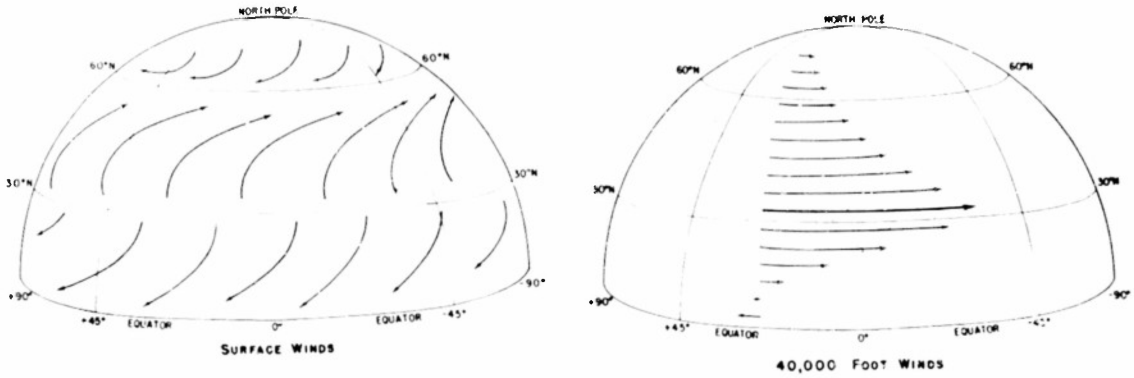


Figure 26. Schematic illustration of principal wind system over the Northern Hemisphere at the earth's surface and at 40,000 feet. (Namias [57])

westerlies. The surface wind pattern also indicates a zone of easterlies in polar regions and another in the subtropics. The variation in strength of these flows can be measured by calculating the average wind speed in fixed geographical belts or by computing "roving indices" as defined by Stone and Willett [77].

Six indices are computed to ascertain the state of the circulation in the subtropical, temperate, and polar belts of the western hemisphere at sea level and 700 mb. The subtropical and polar winds usually are easterlies at the surface, while the remaining four indices are generally westerlies. The indices, expressed in meters per second, are found by the geostrophic formula from the average pressure differences between latitudes 70°N and 55°N, 55°N and 35°N, and 35°N and 20°N. Due to inadequate data in the eastern hemisphere and the effect of the Asiatic monsoon the indices are obtained only for the western hemisphere (0° to 180°W).

The use of roving indices is limited in that it involves the double problem of forecasting both locations and strengths of the wind currents. Consequently such indices are only considered qualitatively by inspection of zonal wind profiles showing the average westerly flow at each latitude of the western hemisphere.

It is also of interest at times to deal with indices or profiles for more restricted longitude sectors as, for example, North America. In general, however, it has been found that the state and development of the general circulation is better related to large-scale indices.

One striking feature of the normal wind field (Figure 26) is the existence of a marked peak in the north-south profile which has been defined as the "jet stream". This jet has been characterized as a meandering current in the atmosphere usually found at or near the tropopause. It exhibits wide variations in space and time.

Figure 27 illustrates the normal jet stream (solid arrows) and mean isotachs

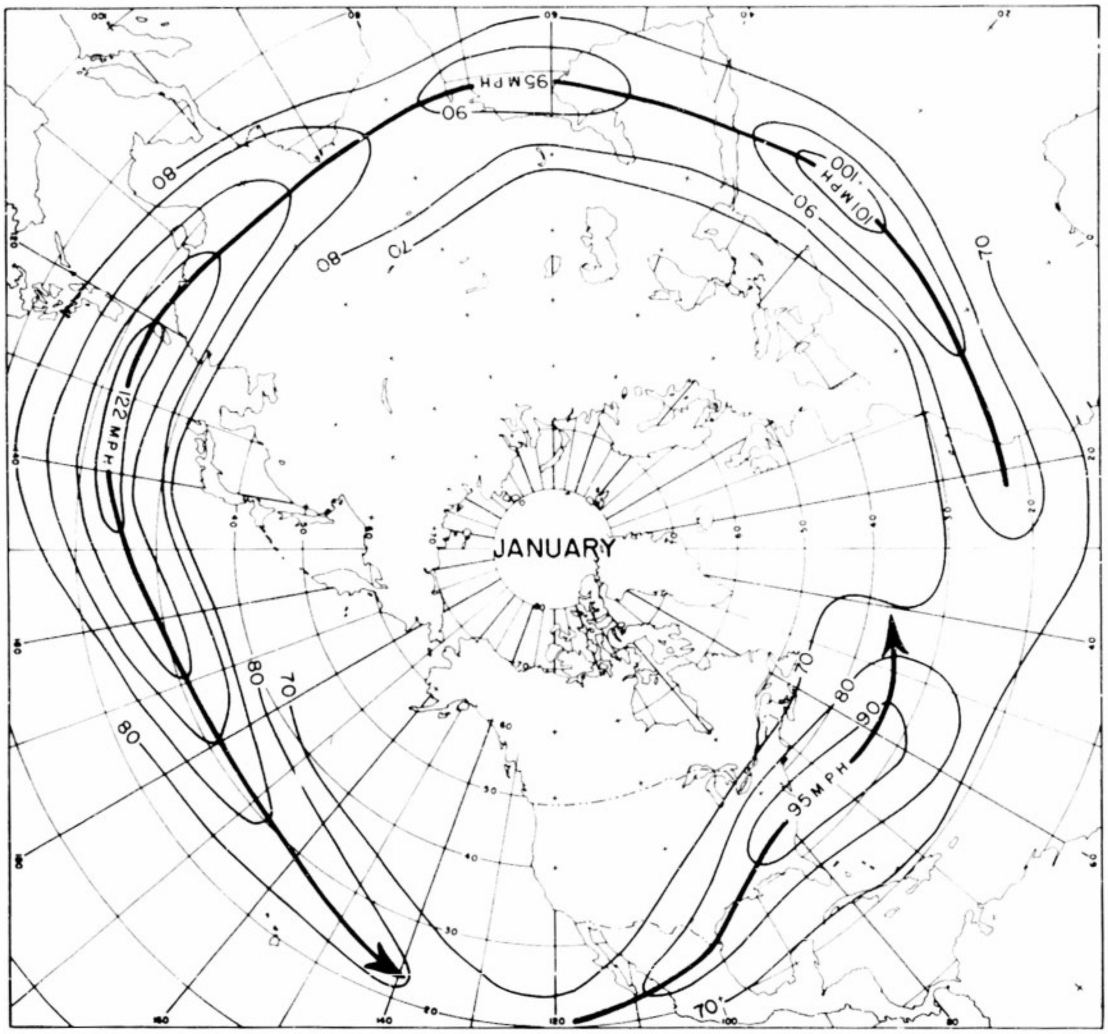


Figure 27. Mean position and intensity (mph) of zonal jet streams found over the Northern Hemisphere between 11 and 14 km in January. (Namias [57])

for the month of January. The data for this map were observed between 11 and 14 km. The geographical location and the intensity of the maximum winds shift with the seasons, being found farthest north and weakest in the late summer and at its most southerly position and strongest in late winter.

There are also significant changes in the position and intensity of the jet within seasons. The time variation of the latitude of the jet in the winter of 1947 is shown in Figure 28. It is evident that a pronounced shift of latitude can take place within a period of a few weeks.

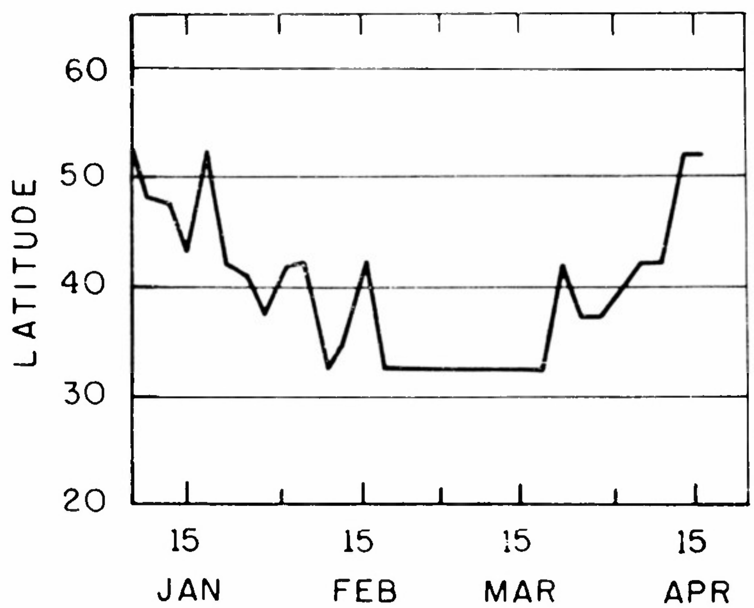


Figure 28. Latitudinal displacement of circumpolar jet from January through April, 1947. Computed from five-day means at 700-mb between 0° westward to 80°W. (Namias [57])

The non-seasonal expansions and contractions of the circumpolar vortex, and the corresponding shifting of the jet stream, have been discussed by Namias [56] as a recurring "index cycle." This cycle, as it progresses, is intimately connected with the general circulation and the weather.

In the first stage of an index cycle (Figure 29) the jet stream is typically in a far northerly position and the circulation is marked by fast westerlies or "high index" conditions. The troughs and ridges (to be discussed below) are of small amplitude and the cold air of polar regions is confined to high latitudes.

As the jet stream begins its initial expansion the cold air pours southward, forming troughs in the preferred regions off the Siberian coast and east of the Rocky Mountains.

The third stage of the cycle is typified by the development of large-amplitude

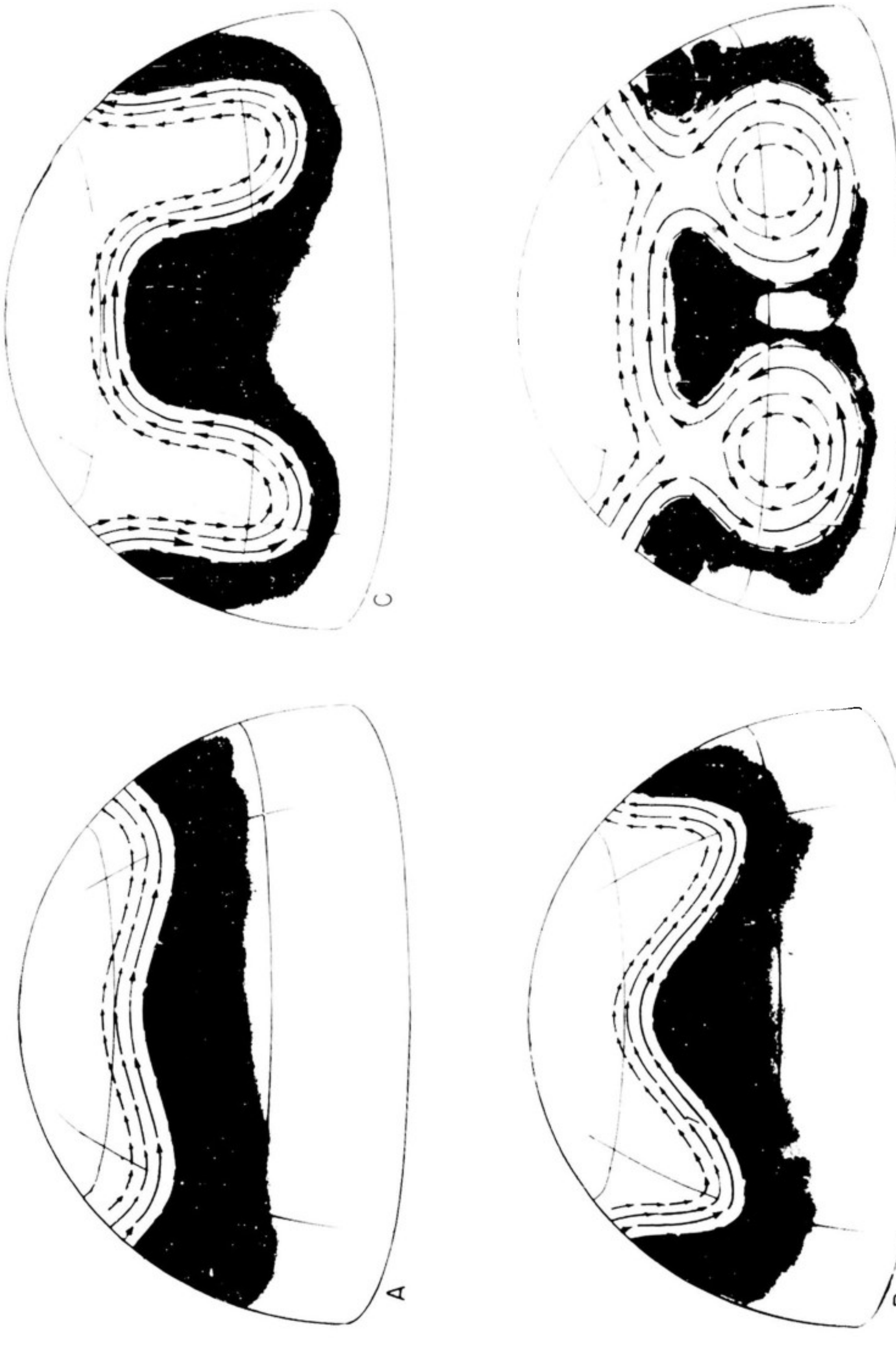


Figure 29. Schematic representation of four stages in the index cycle. (a) high index; (b) initial decline; (c) further decline; (d) low index. (Namias [57])

waves and a strong meridional circulation.

By its fourth phase the index cycle has produced a complete reversal from the initial high index state to a "low index" pattern. The circulation is now of a cellular nature with cut-off cold lows at lower latitudes and warm highs in the north. This is a period of topsy-turvy weather when, for example, temperatures in the far north may be higher than those in the southern United States.

Although the values of the various indices and the wind profiles do not in themselves uniquely determine the circulation pattern and the associated weather, they nevertheless afford valuable clues which the extended-period forecaster must consider in evaluating the situation and preparing a prognosis.

Forecasting the indices and features of the zonal wind profiles involves a combination of statistics, physical reasoning, and qualitative appraisal of various parameters on the basis of empirical rules.

Long-term trends often are apparent in such processes as the index cycle. These and shorter-term trends can be discovered objectively through the use of regression equations. Due to the serial correlation present in pressures at a given point and the effect of the normal, it has been possible to obtain quite accurate estimates of the indices for the five-day mean period a half-week in advance and also fairly reliable indications for the forecast period, the five-day period, a full week ahead. The statistics provide an objective determination of trends which may also be discovered subjectively by a comparison of the latest available data with the previous mean and with the normal.

It has been noted by Namias and Clapp [55] that "confluence", the flowing-together of two atmospheric currents with sharply differing thermal characteristics, produces an intensification of the westerlies. It therefore behooves the forecaster to discover any existing confluence mechanisms and to predict the development of a confluence pattern during the forecast period. Confluence is most often brought about when the northwesterly flow on the east side of a high latitude ridge meets the southwesterly current from a low latitude trough to the south of the ridge.

The forecaster must also consider the future motion of blocking waves which may be present together with factors favoring the genesis of blocking. It has been found that a useful concept of blocking, in regard to extended-period forecasting, is a lowering of the zonal index. As a wave of blocking proceeds westward the lowering of the westerlies may be found progressively further upstream; at the same time the zonal index ($35^{o}N$ to $55^{o}N$) generally recuperates as the blocking relaxes in the downstream sector.

Another device of less importance for forecasting the indices (and the wind profile) is the examination of the hemispheric profiles of pressure change. Occasionally a wave-train of pressure surges appears in the change profile and moves regularly from the pole toward the equator or from the equator toward the pole. Profile waves, when established, may be of empirical value in supplementing other prognostic indications.

2. Predicting the Mean Circulation.

a. By Physical Methods. An examination of the normal and five-day mean upper-level maps reveals a circumpolar whirl of westerlies on which a quasi-sinusoidal

wave pattern is impressed (see Figure 30). The nature of these long waves in the westerlies, established in part by the distribution of continents and oceans over the earth's surface, has been studied theoretically by many investigators. Empirically the waves are found to exhibit continuance motions either westward or eastward, changes in amplitude, disappearances, and geneses.

Figure 31 showing a series of waves in the westerlies, is a schematic model of the westerly drift over the northern hemisphere. The trough off the Asiatic coast results from the extremely cold Siberian air masses which are forced over the warm Japanese current in winter. This initial disturbance of the westerly current creates a series of waves downstream.

The waves in the westerlies have an important effect on the weather as cold-air masses are transported southward by the northwest winds behind the troughs and warm air masses are brought northward ahead of them. As a result of the convergence of the dissimilar air masses, strong frontal discontinuities are established and result in most of the storms of temperate latitudes.

Rossby [66], on the basis of the vorticity theorem and certain simplifying assumptions, found that the speed of a westerly wave is dependent upon the latitude, the zonal velocity of the current in which the wave is imbedded, and on the wave length. The mathematical relation is

$$c = U - \frac{\beta L^2}{4\pi^2},$$

where c is the speed of the wave, U is the strength of the zonal westerlies, L is the wave length, and β is the northward rate of change of the Coriolis parameter. Similar expressions have been derived by Haurwitz [33] and subsequent investigators on the basis of less restrictive assumptions than those applied by Rossby.

From the above formula it is apparent that short waves in fast zonal westerlies (high index) travel rapidly eastward while long waves in weak westerlies (low index) travel slowly eastward or even retrogress.

In practice the wave length is measured from a given trough to the next trough upstream at the same latitude. If the wave system is quasi-symmetrical the half-wave length from the trough to the adjacent upstream ridge may be measured and doubled. Since a symmetry is frequently observed, judgment must be exercised in deciding whether the upstream ridge or trough will be the effective agent in wave adjustment according to the formula.

Research on five-day mean charts at the 10,000-foot level has shown (Namias and Clapp [51, 52]) that while the Rossby formula gives wave speeds which correlate well with observed motion, in general the computed displacements require eastward correction, presumably because the level of non-divergence is usually above 10,000 feet. It is possible to derive regression equations which incorporate suitable compensations for various latitudes and different seasons of the year. These modifications of the theoretical formula are found to produce more accurate estimates of wave motion. The Rossby formula has also been applied successfully to daily charts by Cressman [23] who measured the strength of the zonal westerlies at 600 mb, close to the mean level of non-divergence.

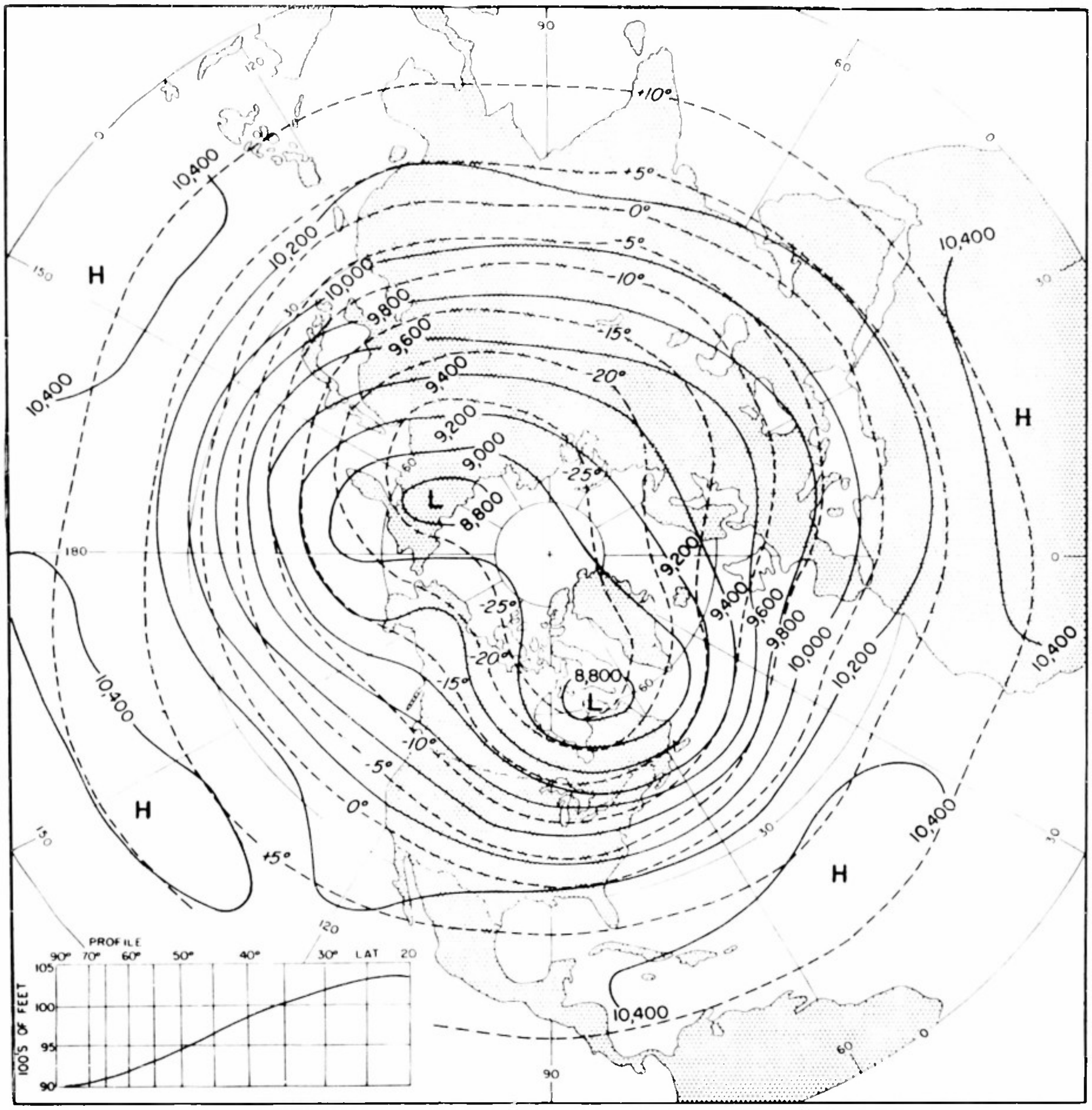


Figure 30. Normal contours at 700 mb for January. (Namias [53])

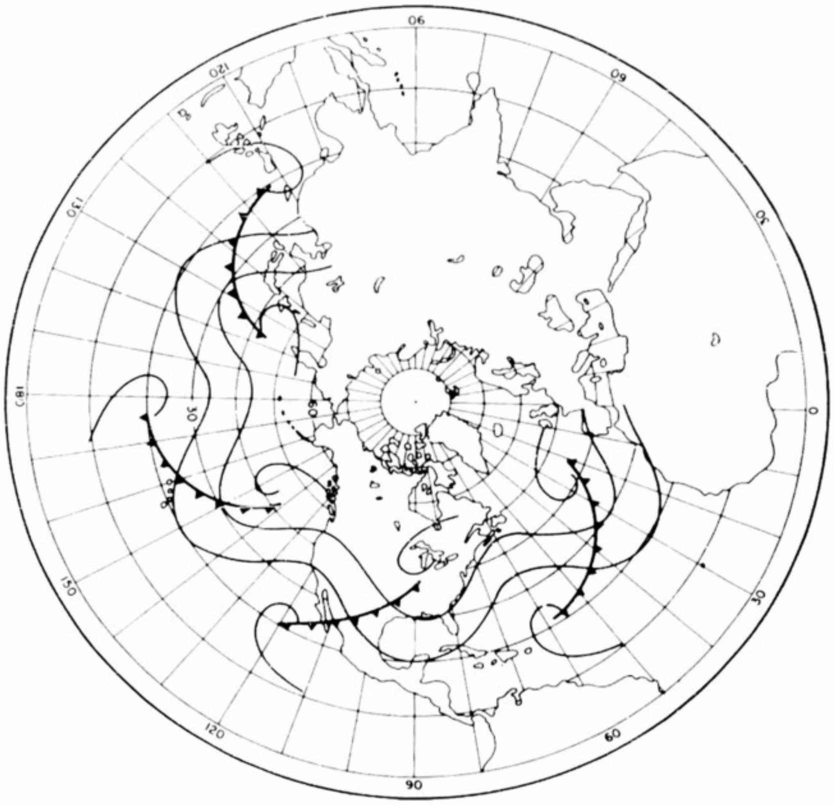


Figure 31. Schematic representation of the wave pattern in westerlies aloft with low index. Heavy lines indicate induced polar front. (Namias [53])

The relationship between wave length and resulting trough displacement has been studied empirically, and regression equations and seasonal graphs have been prepared for latitudes 35°N, 45°N, and 55°N for use in forecasting. Separate graphs are required for different geographical areas due to varying normal topographical and solenoidal effects. In practice the relationship is used to estimate full-week trough displacements on the last observed five-day mean chart and also to estimate half-week motions on the trend map.

The effectiveness of the wave length may be lost occasionally when abrupt changes occur in the over-all pattern. This is particularly noticeable at times of trough genesis or disappearance. For example, two troughs may separate to a distance equal to the stationary wave length (for which zero motion is indicated for the downstream trough). Any further increase makes the wave length excessive, hence an adjustment, often in the form of a reversal of the tendency for the two troughs to move apart, must take place. Excessively long wave lengths may also be compensated by the appearance of a new trough between the two existing extended troughs. Since the new wave lengths will then usually be too short, a rapid displacement of the downstream

trough often follows.

It must be realized that the wave length graphs cannot be used in a completely localized fashion. Rossby [68] demonstrated theoretically that energy can be dispersed at speeds quite different from that of the zonal current. As a result, changes in any part of a planetary wave system may cause rapid readjustments in the pattern in distant regions. It therefore becomes necessary to integrate wave motions expected in all parts of the hemisphere before drawing conclusions about local long-period developments.

As an adjunct to the use of the wave-length concept, relationships between wave length and wave amplitude have also been developed. Bortman [11] found that on five-day mean charts long wave lengths are associated with large amplitudes over North America while short wave lengths are correlated with smaller amplitude systems. Klein [40] obtained similar results for monthly mean charts in North America; the relationship was not found to hold over the Atlantic and Pacific Oceans.

The vorticity theorem provides a second approach to the problem of wave developments. Rossby [67] has shown that the trajectory of an air parcel can be computed if it is assumed that the vertical component of the absolute vorticity remains constant. By means of a slide rule developed by Bellamy it is possible to estimate the wave length and amplitude (and also the timing) of the sinusoidal path to be followed by an air parcel if the initial latitude, speed, and direction of the flow in which the parcel is imbedded are known. The lateral shear of the current is neglected by considering only broad currents with negligible shear. The curvature of the current is also disregarded by working with straight flow, usually at an inflection point of the existing flow pattern. The use of these trajectories is given in [30] and [104].

An improved computer has been developed by Wobus (1951). This is a mechanical device which can be set at any point of a constant pressure map where shear and curvature are absent, and adjusted for the variables which enter into the determination of the constant absolute vorticity trajectory. This differential analyzer, popularly called a "wiggle-wagon," solves the vorticity (differential) equation and automatically traces the desired trajectory on a given map projection, taking account of the earth's sphericity. Tables based on the "wiggle-wagon" have been published [103], which make use of a slide rule or "wiggle wagon" unnecessary.

In forecasting operations, trajectories are obtained at the 700-mb and 500-mb levels for daily charts [30, 104]. These trajectories indicate the tendency for ridge and trough systems to remain stationary or shift position in response to well-developed currents in other areas; they may also indicate changes in amplitude. At times vorticity trajectories may illustrate temperature advection, the advent of confluence, or the development of new troughs or ridges and cut-off highs and lows.

In a qualitative fashion the solenoidal term also is considered in the operational routine of the U. S. Weather Bureau Extended Forecast Section. Charts of the departure from normal of temperature at the 700-mb level are constructed on a mean and daily basis. Similar anomalies of the daily thickness pattern (1000 mb to 700 mb) are obtained. These charts depict the available pools of relatively warm and cold air associated with ridge and trough developments. It is generally considered that strong cold air advection is associated with trough deepening while ridge building is accompanied by warm air advection. A comparison of the mean and daily

charts may also provide clues of temperature trends which are then related to circulation developments.

b. Trend and Kinematic Methods. Two of the basic steps in weather forecasting are the evaluation of existing trends in meteorological data and their projection into the future. Short-period forecasters rely heavily on trends by extrapolating the movements of highs or lows, frontal systems, anallobars or katallobars, and by considering three-hourly tendencies on the last available map. In extended-period forecasting, longer-period trends usually are considered, preferably those associated with such large-scale or semipermanent features of the atmosphere as the "centers of action". Many of these methods have already been discussed in the sections on statistical methods, selection of analogues and types, and various evolutionary methods.

The Extended Forecast Section of the U. S. Weather Bureau has devised a special method of measuring the existing long-period trends quantitatively. It has been referred to as the kinematic, regression, or trend technique. It incorporates three basic meteorological principles: (a) persistence or serial correlation in pressure (and other continuous meteorological functions), (b) tendency for pressure to return to normal, and (c) determination of future weather by past and present performance of the atmosphere.

The concept of serial correlation is basic to all phases of forecasting by the "mean-map" technique. It is relied on most heavily in the delineation of large-scale atmospheric trends and the construction of the daily series of prognostic charts. Due to serial correlation or the persistence in meteorological data, the middle day of an extended-forecast period will bear the closest resemblance to the mean chart for the entire period. Namias and Clapp [50] have demonstrated this relationship by computing correlations using sea level and 10,000-foot data between the five-day mean chart and each of the 10 daily charts making up the mean. The results show that the middle maps (5 and 6 are the most highly correlated with the mean chart, (see Table 6).

TABLE 6

Observed Correlation Coefficients between the Five-day Mean Chart and Each of the 10 Daily Maps Making it up.

	1	2	3	4	5	6	7	8	9	10
Sea Level Maps	.56	-	.67	-	.71	.78	-	.78	-	.59
10,000-foot Maps	.81	-	.88	-	.92	.88	-	.82	-	.82

Namias further showed [53] that the serial correlation between successive pressures at a point appears to follow the exponential die-away curve:

$$(1) \qquad r_n = r_1^{\,n}$$

where r_1 is the one-day lag auto-correlation coefficient and r_n is the correlation between the current pressure and the pressure n days later (Figure 32). He uses

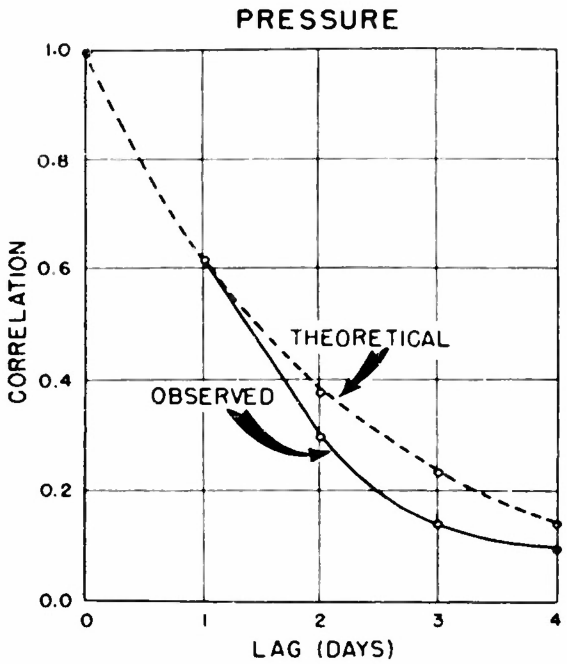


Figure 32. Lag correlations for pressure at 10,000 feet at 40°N 90°W during 1944-1945. Solid curve shows observed values. Broken curve shows theoretical values given observed lag correlation for first day and assuming exponential decrease. (Namias [53])

the values of this theoretical curve to explain the resemblance between the chart on the middle day of the period and the mean chart for the period:

"Let us assume that a mean is composed of five-day maps and at one point the pressures on succeeding days are P_1, P_2, P_3, P_4 and P_5. Let us further assume that the lag correlations are given by the theoretical curve in Figure 32; that is

$$r_1 = 0.62$$
$$r_2 = 0.38$$
$$r_3 = 0.24$$
$$r_4 = 0.15$$
$$r_5 = 0.09$$

Then the first day's value (corresponding to the first day's map) will have the following correlations with each of the other four days: 0.62, 0.38, 0.24 and 0.15. The last value in the series (corresponding to map 5) will also have these correlations with the other values making up the mean. The correlations of the second and fourth values in the series with each of the four other values will be 0.62, 0.62 (two 1-day lags) 0.38 and 0.24. The correlation of the third value (the middle value) with each of the others in the series will be 0.62, 0.62 (two 1-day lags) and 0.38, 0.38 (two 2-day lags). Thus, the middle map in the series has the greatest total correlation with the series of five maps and hence with the mean."

The exponential lag correlation can be used in estimating large scale trends in the atmosphere. The makeup of the 700-mb five-day mean chart can be used for illustration. This chart is an average of 10 twice-daily charts as shown in equation 2.

$$(2) \quad \bar{h} = 1/10\ (h_{-10} + h_{-9} + h_{-8} + h_{-7} + h_{-6} + h_{-5} + h_{-4} + h_{-3} + h_{-2} + h_{-1})$$

In this notation h denotes the daily 700-mb height, while the subscript identifies the individual map in the series. Thus h_o is the height on the last available map on forecast day (0300Z), h_{-1} is the height on the map 12 hours earlier (1500Z of preceding day), h_{-2} is the height on the map 24 hours earlier (0300Z of preceding day), and so forth. The mid-period of this five-day mean chart is centered around maps which were observed three days ago. In forecasting it is desirable to consider the most recent trends possible, at least those centered about today's map; i.e., a mean map $\bar{h}_{\frac{1}{2}}$ one-half week in advance of the mean chart constructed from the latest observed data. The following data would constitute such a mean chart:

$$(3) \quad \bar{h}_{\frac{1}{2}} = 1/10\ (h_{-4} + h_{-3} + h_{-2} + h_{-1} + h_o + h_1 + h_2 + h_3 + h_4 + h_5)$$

where h_1 is the daily 700-mb height 12 hours after the last daily map h_o, h_2 is the height 24 hours later, etc. The first five terms of this equation have already been observed and the remaining five values represent future data. The unknown portion of this equation can be estimated statistically by using the principles of serial correlation and the tendency for pressure to return to normal. Experiments with observed data have revealed that persistence from the last observed map (h_o) can be relied upon heavily for the first few unknowns and the seasonal normal (N) for the latter ones. The exact proportion of h_o and N entering into the estimation of each unknown is determined by applying the exponential lag correlation formula (equation 1). The most suitable expression for estimating the sum of the five unknown values has been found to be $3h_o + 2N$. Substituting this expression in equation 3 the formula becomes

$$(4) \quad \bar{h}_{\frac{1}{2}} = 1/10\ (h_{-4} + h_{-3} + h_{-2} + h_{-1} + 4h_o + 2N)$$

Values of $\bar{h}_{\frac{1}{2}}$ (called the "half-week aggression") are computed from this equation by machine methods for each 10-degree intersection of latitude and longitude. These are plotted and analyzed in the same fashion as the observed five-day mean values and the resulting chart is the trend map.

The correlations between the height patterns on the trend map and the observed mean it is supposed to represent, were tested on random independent data without removing the effect of the normal, and the extremely high correlation of 0.985 was found. In fact, the trend map gives such an accurate estimate of the next one-half week observed map that it is often used as a "jumping-off-point" for making the mean forecast for the period one full week ahead (or one-half week after the trend chart). It is also used as a base for the application of physical methods of prognosis such as vorticity trajectories, wave-length graphs, and temperature-advection calculations.

Height tendencies at 700 mb, centered about the middle day of the last observed five-day mean chart (kinematic chart) and the middle day of the trend chart are also computed and analyzed. The time interval of two days has been chosen for these tendencies. Therefore, they represent the difference between the mean chart one day before and the mean chart one day after the middle day of the period about which they are centered. The equations for these tendencies are

derived by applying the lag correlation (equation 1) to the unknown (future) heights, and may be written as follows:

(5) Kinematic $T_o = 1/10\ (2h_o + h_{-1} + h_{-2} - h_{-9} - h_{-10} - h_{-11} - h_{-12})$

(6) Trend $T_{\frac{1}{2}} = 1/10\ (2h_o + 2N - h_{-3} - h_{-4} - h_{-5} - h_{-6})$

Either of these tendencies can be utilized in a fashion similar to the use of the three-hourly tendencies in short-range forecasting. In the forecast routine, computations are made on the kinematic and trend charts from Petterssen's equations which are commonly applied to daily charts. (See Petterssen [63] pp. 384-386.)

(7) $$S = \frac{N}{2} \quad \frac{T^{1/2} - T^{-1/2}}{(h^1 - h^o) + (h^{-1} - h^o)} L$$

where S = kinematic displacement, N the time interval of forecasting days, ($T^{1/2}$) and ($T^{-1/2}$) the tendency one-half a length unit (L) ahead and one-half a unit behind the point of computation, and h^1, h^{-1}, h^o the height value one full length unit ahead, behind, and at the point of computation, respectively.

Displacement computations are usually made along latitude circles. In picking points suitable for computations and in choosing the best unit of length, the criteria applied are similar to those used in daily forecasting. Such computations have limitations. They are most suitable to charts having well marked troughs and ridges, with sharp height profiles and strong tendency fields, and with the centers well removed from the trough and ridge lines. They are less reliable when made on flat patterns or those with height-change centers located so close to the ridge and trough lines that a slight relative displacement may change the indicated direction of motion.

The regression technique has recently been extended (Klein [39]) to provide a map similar in all respects to the trend chart except that it is centered two days later. The 700-mb height of this map, called the extended height, is considerably less accurate than the height on the trend map because it includes a greater number of unknowns. The corresponding two-day height tendency, however, which is called the projected tendency, is only slightly less accurate than the trend tendency. It is therefore of considerable value in indicating changes to be expected later in the period. When compared to the tendency fields on the kinematic and trend maps, it often gives valuable clues about the possibility of reversal of existing trends, relative motion between the tendency and height fields, and deepening, filling, or acceleration of systems. The equations for computing the projected tendency and extended height are relatively simple and are listed in Table 7.

Thus three different tendencies together with their corresponding height fields are available for kinematic computations. Their properties are summarized in convenient form in Table 8.

TABLE 7

Complete List of Statistical Equations Used in the Forecast Routine of the Extended Forecast Section

Element	Name of Factor	Equation
	(a) For the five-day forecast:	
700-mb height	Latest observed mean	$1/10 \sum_{-10}^{-1} h$
	Half-week regression	$1/10 [4h_0 + 2N + \sum_{-4}^{-1} h]$
	Extended height	$1/10 [5h_0 + 4N + h_{-1}]$
	Full-week regression	$1/10 [2h_0 + 8N]$
	Kinematic tendency	$1/10 [2h_0 + \sum_{-2}^{-1} h - \sum_{-12}^{-9} h]$
	Trend tendency	$1/10 [2h_0 + 2N - \sum_{-6}^{-3} h]$
	Projected tendency	$1/10 [3N - \sum_{-3}^{-1} h]$
Sea-level pressure	Latest observed mean	$1/10 [\sum_{-10}^{-1} p]$
	Half-week regression	$1/10 [3p_{-1} + 3N_p + \sum_{-4}^{-1} h]$
	Full-week regression	$1/10 [2p_{-1} + 8N_p]$
	Trend tendency	$1/10 [1p_{-1} + 3N_p - \sum_{-6}^{-3} p]$
700-mb temperature	Latest observed mean	$1/10 \sum_{-10}^{-1} t$
	Half-week regression	$1/10 [3t_0 + 3N_t + \sum_{-4}^{-1} t]$
	(b) For the monthly forecast:	
700-mb height	Latest observed mean	$1/60 \sum_{-60}^{-1} h$
	Half-month regression	$1/60 [6h_0 + 24N' + \sum_{-30}^{-1} h]$
	Extended height	$1/60 [6h_0 + 44N_1 + \sum_{-10}^{-1} h]$
	Kinematic tendency	$1/60 [5h_0 + 5N_{\frac{1}{2}} + \sum_{-10}^{-1} h - \sum_{-70}^{-51} h]$
	Trend tendency	$1/60 [20N_1 - \sum_{-40}^{-21} h]$
	Projected tendency	$1/60 [20N'' - \sum_{-19}^{-0} h]$

(Continued on next page)

TABLE 7 Cont'd

Complete List of Statistical Equations Used in the Forecast Routine of the Extended Forecast Section

Element	Name of Factor	Equation
Sea-level pressure	Latest observed mean	$1/60 \sum_{-60}^{-1} p$
	Half-month regression	$1/60 [4p_{-1} + 26N'_p + \sum_{-30}^{-1} p]$
	Trend tendency	$1/60 [20N_{1(p)} - \sum_{-40}^{-21} p]$

(NOTE: h_o and t_o are read from the latest daily 700-mb map (0300Z) available on forecast day; h_{-1} and t_{-1} are read from the map drawn 12 hours before h_o at 1500Z on the day before forecast day; and p_{-1} is read from the 0030Z map on forecast day. $N_{\frac{1}{2}}$ is the normal for the month ending a half-month after forecast day; N_1 is the normal for the month ending a full month after forecast day: N' is the average of the two normals, $N_{\frac{1}{2}}$ and N_1, and N'' is the average of the two normals, N_1 and the normal for the month ending one-and-a-half months after forecast day).

TABLE 8

Comparison of Three Charts Available for Kinematic Computations for Five-day Forecast

	Kinematic	Trend	Projected
Time centered	3 days before h_o	on h_o	2 days after h_o
Number of days computation is extrapolated	7	4	2
Accuracy of tendency (correlation coefficient)	0.95	0.68	0.65
Accuracy of corresponding height anomaly (correlation coefficient)	1.00	0.84	0.70

It should be noted that the kinematic map most accurately portrays what it is supposed to portray, since it is computed almost entirely from observed data. On the other hand, it is centered the earliest in time and therefore requires the longest

period of extrapolation of the instantaneous velocity computation. The projected tendency and extended height, in contrast, are the least accurate quantities but the most advanced in point of time. The trend map is intermediate between the kinematic and projected in all these respects.

The regression technique can be applied to any continuous meteorological element. Trend charts are currently being constructed for sea-level pressure, 700-mb height, and 700-mb temperature. Kinematic and projected tendencies are prepared for 700-mb height only. In addition, half-week and full-week regression values are regularly computed for six circulation indices at sea level and 700 mb. The entire technique has also been applied successfully to the monthly forecast procedure (Klein [37]) where the regression equations are similar in most respects to those used in the five-day forecast. A significant difference, however, is the assumption that the normal 700-mb height is constant for any five-day forecast period but varies with time for the monthly forecast.

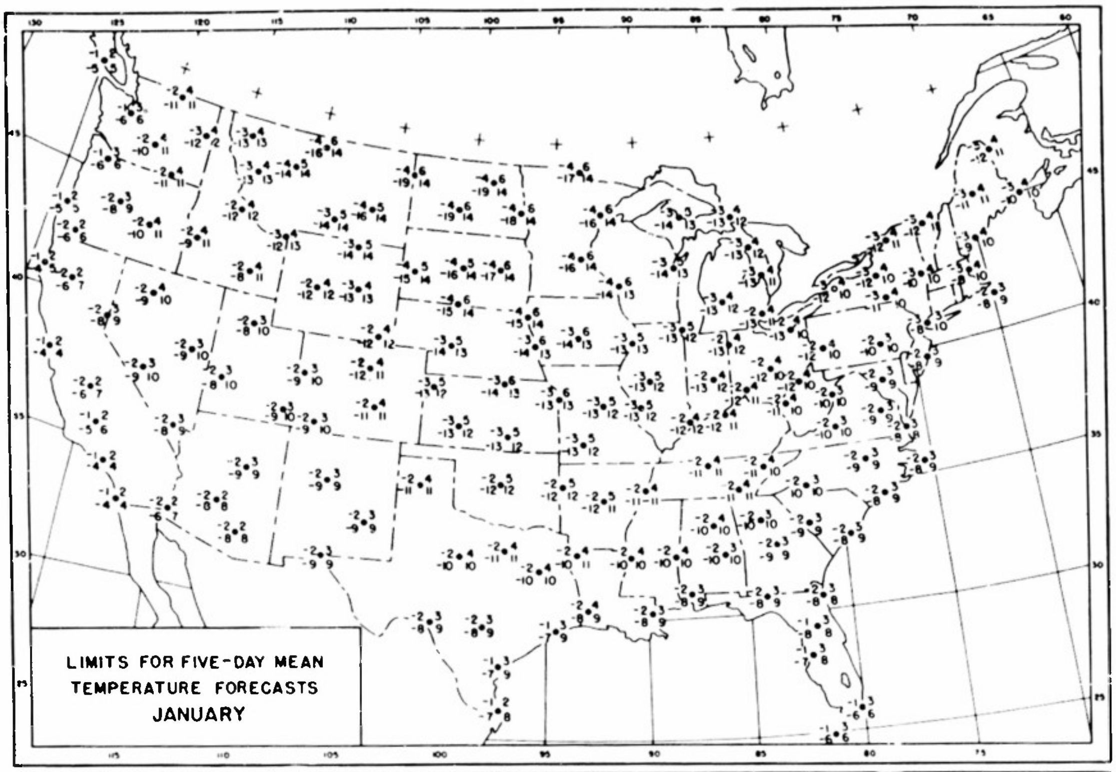
In general, the trend and kinematic maps give the forecaster a quick, quantitative appraisal of long period trends which are often difficult to obtain by mere inspection. Forecasts made using the kinematic procedure are relatively objective, but considerable experience is needed to determine when and how to use them. They have been found to be most reliable when they are in agreement or can be integrated with the forecasts made using physical or dynamical reasoning.

On forecast day an auxiliary forecaster makes a prognostic 700-mb five-day mean chart using kinematic techniques, while another forecaster makes an independent 700-mb five-day mean prognosis based on physical indications. These forecasters then brief the official forecaster whose principal job is the integration of physical and kinematical considerations into a consistent, logical, mean prognosis.

3. Interpreting the Pattern in Terms of Weather. After the mean 700-mb prognosis has been completed, anomalies of temperature and precipitation are estimated. Temperature anomalies are given in terms of above, below, near, much above, and much below normal. The numerical limits defining these ranges are called "class limits" (see Figure 33) and are based on a statistical analysis of past records so that each of the classes above, below, and near normal has a probability of occurrence one fourth of the time and the other classes one eighth of the time. For precipitation the limits have been determined so that each of the classes light, moderate, and heavy has a probability of occurrence one third of the time. Such class limits of course, vary from month to month and from place to place.

In the forecasting routine, temperature and precipitation anomalies are assumed to be by-products of the contour prognosis. Such an assumption is made by short range forecasters the world over, and is basic to the mean circulation technique. In other words, regardless of how it is made up, and irrespective of the trends within the period, the mean circulation pattern is assumed to have a definite physical meaning in terms of actual weather [35]. Numerous recent statistical studies tend to support this basic assumption (Martin [43, 44], Klein [38]).

Although this assumption is to a considerable extent justified, it has been shown by controlled experiments [14, 58] that if forecasters were provided with the same perfect prognostic charts (observed maps) their forecasts of weather elements would display considerable variance from each other and from the observed weather. However, recent research studies of the Extended Forecast Section of the U. S. Weather Bureau have afforded methods of improving the interpretive process. The studies show that in many respects a mean chart can be interpreted in a similar fashion to a daily chart, i.e., the types of contour patterns which produce abnormal



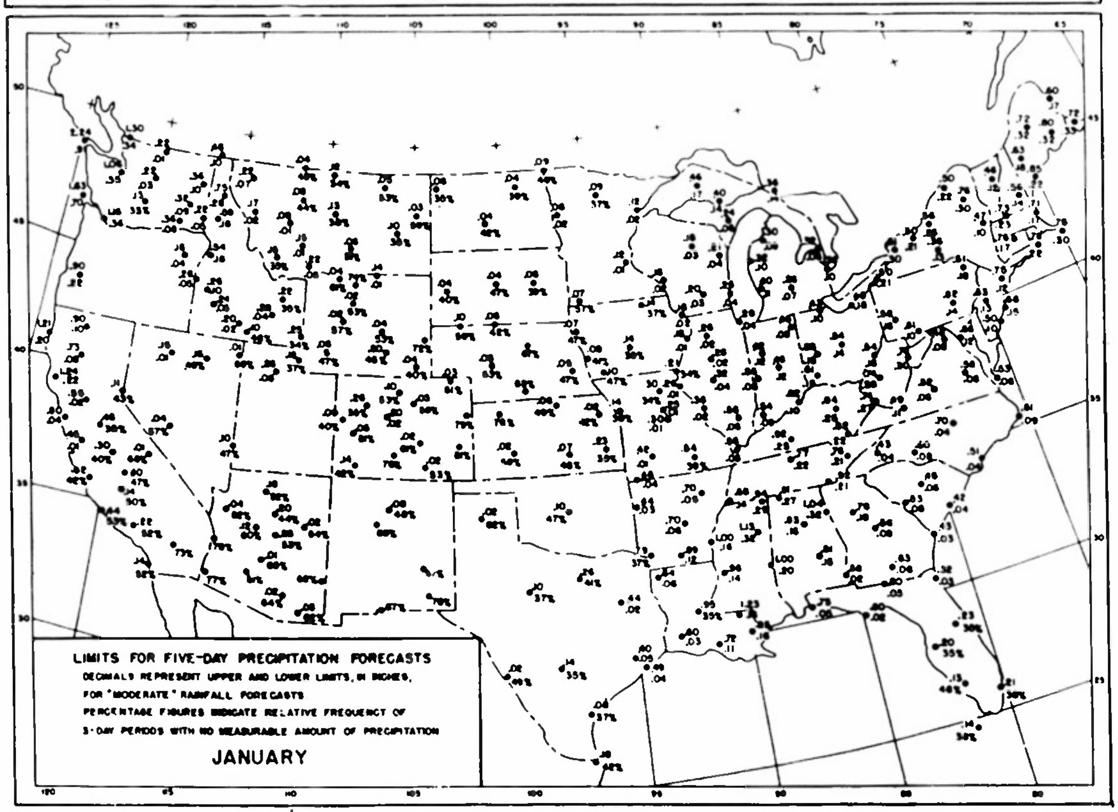


Figure 33. Class limits of temperature and precipitation for the month of January. (Namias [53])

weather on a daily map produce corresponding anomalies on five-day or monthly mean charts.

In general, cold surface-temperature anomalies are found in the northerly flow behind a mean upper-level trough and warm anomalies in the southerly flow ahead of the trough. Heavy precipitation anomalies are generally found to the east of mean troughs with light anomalies to the west (Figure 34). In addition, the amplitude of the trough-ridge system, contour or isobaric curvature, amount of available moisture, temperature contrasts between opposing air masses, topography, season, strength and orientation of the "jet" stream, may effect the temperature or precipitation anomalies.

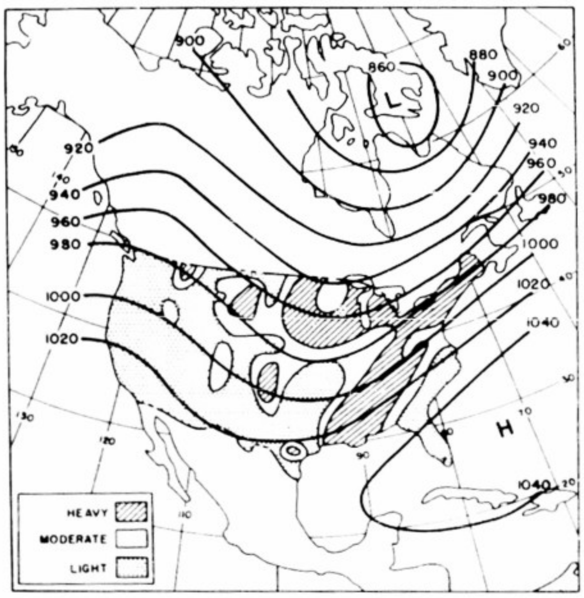


Figure 34. An example of the relation between observed upper-level flow pattern and concurrent precipitation, 6-10 March 1946. The solid lines are 700-mb contours. (Martin and Hawkins [44])

Refined objective techniques have been devised and are currently being used for obtaining the surface temperature anomalies directly from the 700-mb mean prognostic chart. Martin and Leight [43] working with observed patterns, found that monthly surface temperature anomalies could be estimated directly from the 700-mb patterns by a consideration of the height anomalies, contour curvature, and upper-level trajectories. Auxiliary 700-mb five-day mean height-anomaly charts, obtained by subtracting the normal values at each of a network of points from the observed 700-mb five-day mean chart were constructed to aid in this interpretation. It was later discovered that these maps could be used in obtaining an objective estimate of the surface-temperature anomaly, thereby obviating tedious trajectory and curvature computations on the contour chart.

Martin [44] improved and extended this research using the 700-mb five-day

mean height anomaly charts. He computed numerous spatial correlation coefficients between the 700-mb five-day mean height anomalies at numerous points and the contemporary mean surface temperature anomalies at a fixed station for the various seasons of the year. These results show that, in every instance, there are at least two widely separated areas where the 700-mb five-day mean height anomaly is most highly correlated with local surface temperatures (Figures 35 and 36). Additional correlations were then made to see if such relationships between the 700-mb five-day mean height and surface temperature anomalies applied to monthly mean charts. This study showed that in every case the magnitudes of the coefficients of correlation were similar, and that the centers of maxima were located in the same place as those for the five-day mean chart. One of these areas of maximum coefficient of correlation is usually located at or near the particular station while the other one is thousands of miles away. In fact, these distant centers are so well delineated that it seems quite evident that the large-scale features of the atmosphere must be considered in the interpretation of apparently local weather from prognostic charts.

For example, approximately 30 stations located in the United States east of the Rocky Mountains were tested for the winter season, and in each case the surface temperature anomalies were found to be as dependent upon the 700-mb height anomalies in northwestern Canada, at about 60° N and 130° W, as they were upon the anomalies at the particular station itself.

Martin reasoned that when the mid-tropospheric ridge is abnormally strong over northwestern Canada, cold continental air is permitted to invade eastern and central United States causing below-normal surface temperatures in that region. On the other hand, an abnormally weak ridge, over northwestern Canada, permits fast westerly winds, with an accompanying series of frontal waves, to move across the United States-Canadian border and prohibit the intrusion of cold continental air; as a result, mild maritime air masses dominate the central and eastern portions of the United States. Similar reasoning is commonly used in daily forecasting throughout the United States.

The more localized circulation features are reflected by the 700-mb height anomaly near the particular station. Since the 700-mb height anomaly at a station is dependent on the anomaly in the mean virtual temperature of the column of air between 1000 and 700 mb, which is itself highly correlated with the anomalous surface temperature, and since the height anomaly partially designates the character and structure of the air mass in the immediate vicinity of the station, it is not surprising that a high positive correlation coefficient center is found near a given station. This is especially true for continental areas where the variability (variance) of the mean virtual temperatures is great due to the more frequent interplay of contrasting air masses.

When the area near the station and the one far removed are considered together, they significantly define the over-all circulation, the localized character of the circulation, the predominant air masses, the local index, and other factors which influence the surface temperature anomalies.

Such studies as the above have been conducted for numerous stations throughout the United States for various seasons of the year. These reveal that for stations located to the west of the Rocky Mountains, in winter, the surface temperatures are also best defined by two widely separated areas on the 700-mb height-anomaly charts. However, neither of these is located within a thousand miles of the station. One is found in southwestern United States near 35° N 115° W and the other in the northern Pacific near 50° N and 150° W (Figure 36). The height anomaly in the northern

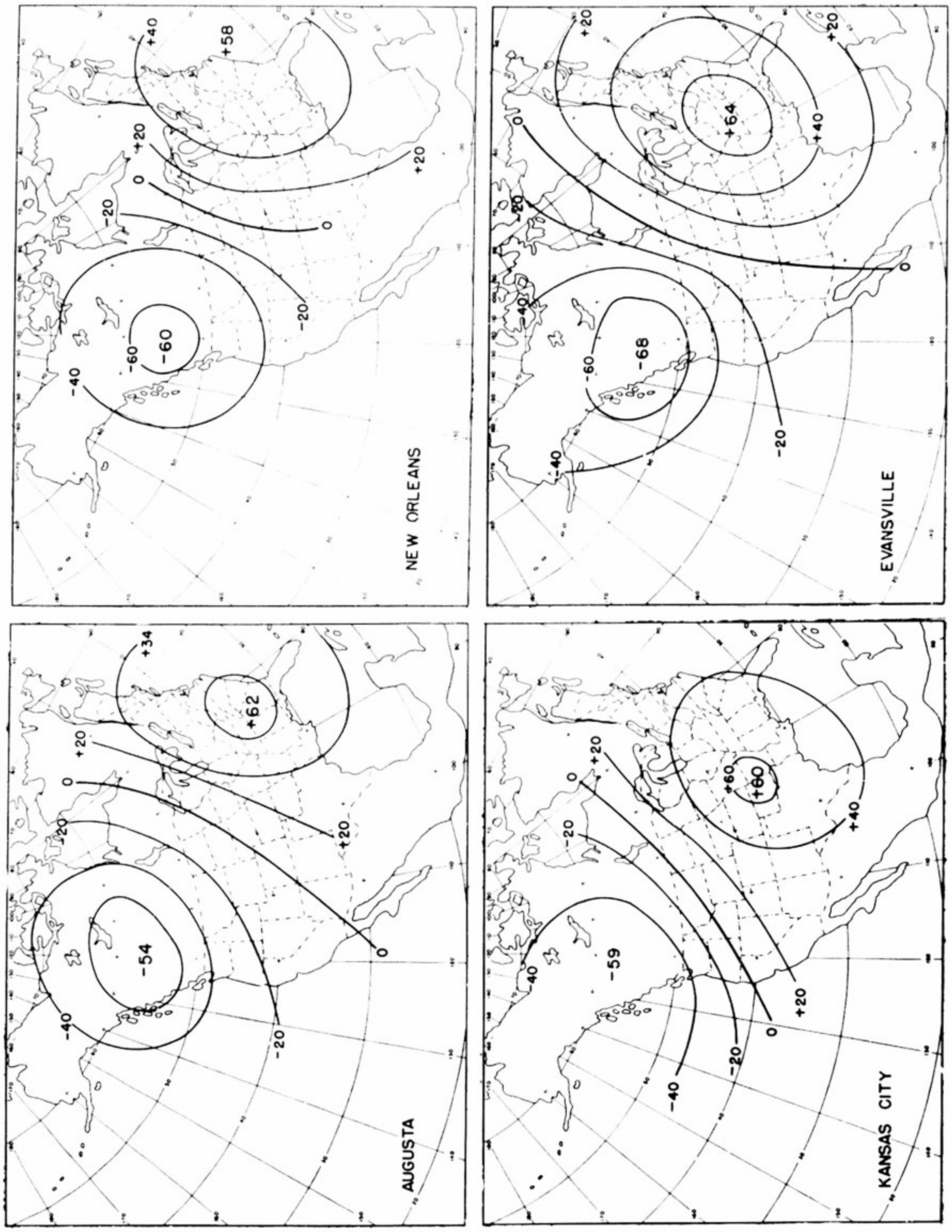


FIG. 35. SPATIAL CORRELATIONS OF 700 MB HEIGHT ANOMALIES AND CONTEMPORARY SURFACE TEMPERATURE ANOMALIES AT STATIONS IN CENTRAL AND EASTERN UNITED STATES. (MARTIN AND HAWKINS [44])

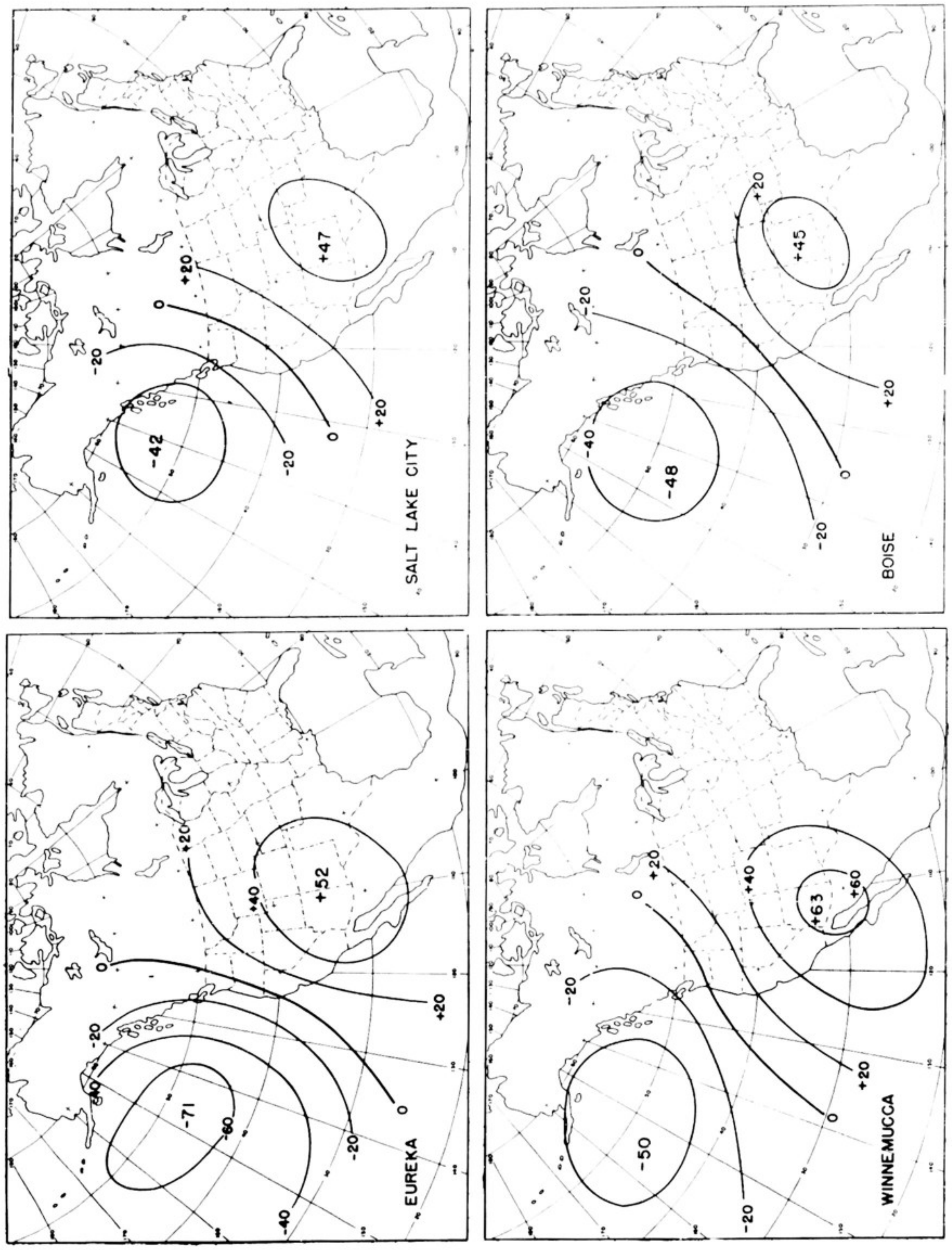


FIG. 36. SPATIAL CORRELATIONS OF 700 MB HEIGHT ANOMALIES AND CONTEMPORARY SURFACE TEMPERATURE ANOMALIES IN WESTERN UNITED STATES. (MARTIN AND HAWKINS [44])

Pacific indicates whether the air affecting the west coast of the United States has a trajectory from the cold northern or warm southern Pacific while the one over the southwestern United States determines the effect that this circulation will have on the surface temperatures over western United States. Such considerations suggest that the over-all large-scale wind directions and velocities are more important than the air-mass structure in the immediate vicinity of the station in determining surface temperatures over western United States.

During the warm season of the year, April through September, more localized parameters are found. The height anomaly at the station becomes relatively more important and those in distant areas less important in estimating surface temperatures from the upper-level flow pattern, due to the characteristically slower motions of air masses, the more localized nature of summer weather, and the weaker temperature gradients between air masses of contrasting source regions. Also, during this season many stations, especially those near the cold coastal waters, have another source region for cold air in addition to the continental polar regions. Temperatures during the warm season are largely a function of such factors as cloud cover, precipitation, air-mass stability and localized wind directions. Therefore, two fixed, widely-separated points on the height anomaly chart are often incapable of defining all these factors. In practice the temperatures are objectively estimated by considering the 700-mb height anomaly near the station and in selected areas, determined in each case in accordance with the direction of the 700-mb isolines of departure from normal height near the station.

The observed surface-temperature anomalies have been plotted and analyzed on scatter diagrams as a function of the observed 700-mb height anomalies in the areas of maximum correlation for numerous stations throughout the United States for the winter and summer season (see Figure 37). From these graphs objective surface-temperature-anomaly forecasts can be made directly and mechanically from either the observed or prognostic 700-mb height-anomaly charts (Figure 38). Such objective anomaly predictions have been tested on independent data and found to be equal to, or better than, the subjective interpretations of the official mean forecasters. However, since the objective graphs do not consider such factors as the "last observed temperature anomalies" or the "abnormalities of a particular year", except insofar as they are reflected in the upper-level pattern, there are times when an experienced forecaster can judiciously insert subjective modifications to the objectively estimated anomalies.

The relationship of precipitation to mean circulation patterns is more difficult to assess. Even here, however, a reasonable degree of success in estimating the precipitation anomalies is achieved by considering such factors as location, intensity and orientation of major troughs and ridge systems, anomalous components of wind, and contour or isobaric curvature.

Smith [76] tested the following parameters on five-day mean maps for their effect upon the contemporary precipitation throughout the United States:

1. Curvature of the isobars on the mean sea-level pressure chart and on the mean 10,000-foot chart. This included the type of curvature (cyclonic or anticyclonic) and the degree or intensity of curvature.

2. The shift in geostrophic-wind direction from the surface to 10,000 feet.

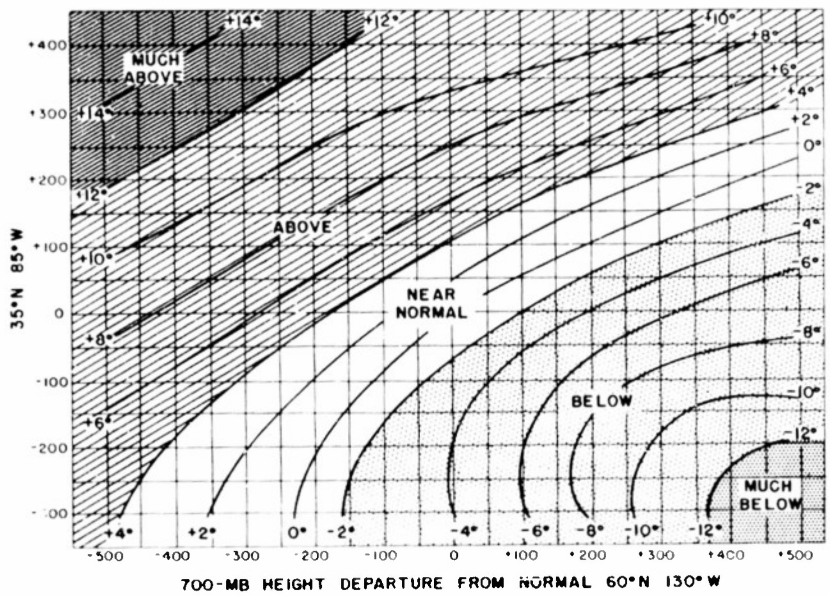


Figure 37. A graph for forecasting surface temperature anomaly at Evansville, Indiana, from the 700-mb five-day mean height anomaly. Ordinate is the departure from normal in feet at 35°N 85°W. Abscissa is the departure from normal in feet at 60°N 130°W. (Martin and Hawkins [44])

3. Moisture supply indicated on a selected mean isentropic chart. This chart pictures the sloping (isentropic) surface along which the moisture-laden air can normally be expected to move.

4. Upslope or downslope motion indicated by winds and contours of elevation on the isentropic chart.

The results of these tests are indicated in Figure 39. Over the Pacific coast, Plateau, and Gulf regions, the moisture supply was the most effective parameter. In the Northeast and the Northern Plains the wintertime precipitation processes seemed to take place below the chosen isentropic level, where perhaps other factors such as upslope motion and overrunning were more important.

The curvatures (both sea level and aloft) were found to be intimately associated with precipitation; cyclonic circulation was associated with heavy precipitation, and anticyclonic circulation with light precipitation. The more intense the curvature, the better was the association and the larger the area covered by the associated precipitation class. The upper-level curvature was slightly more significant than the surface curvature over the Pacific coast and Plateau, the reverse being true in the other three areas.

The change in wind direction between sea level and 10,000 feet worked fairly

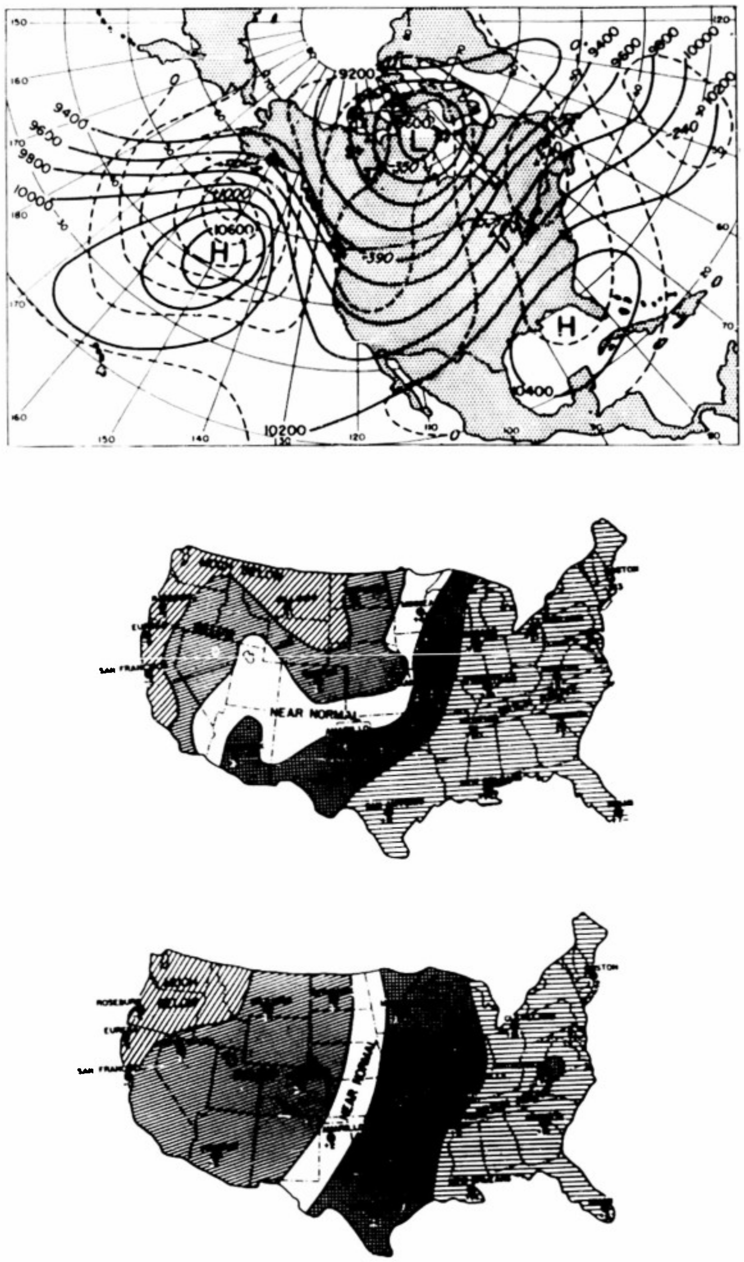


Figure 38. Observed five-day mean 700-mb chart and associated height anomalies 31 December 1949-4 January 1950 (top). Observed temperature anomalies for same period (center). Estimated surface temperature anomalies using objective graphs for numerous stations throughout United States (bottom). (Martin and Hawkins [44])

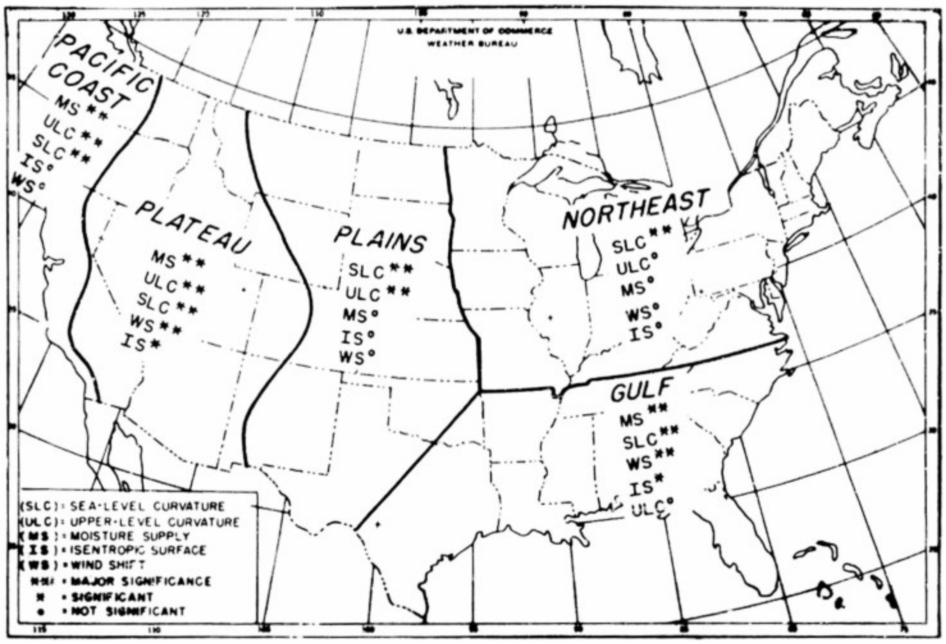


Figure 39. The association of five parameters with winter precipitation over the United States (after Smith). They are listed in order of decreasing association in each region, and the significance of the relationship is shown by the symbol after each parameter, described in the key in the lower left corner. (Martin and Hawkins [44])

well over the Plateau and the Gulf area but was of little significance elsewhere. Finally, a weak relationship was found between upslope and downslope motion on the isentropic surface and precipitation.

A more objective and detailed study was later made by Klein [36, 38] between the upper-level wave patterns and the associated precipitation in the Tennessee Valley. Since this region is fairly representative of those other areas throughout the eastern United States whose main source of moisture is the Gulf of Mexico, the results of this work are applicable to a large portion of the United States.

Occurrences of light, moderate, and heavy precipitation in the Tennessee Valley for five-day mean periods during six winters were investigated with respect to the position of the rainfall areas relative to the mean wave system at 10,000 feet. The results are best demonstrated by the schematic precipitation model of Figure 40.

In addition to the schematic model, which has proved most useful, several other practical relationships were statistically established. These findings indicated:

1. The effectiveness of southerly flow in producing precipitation and northerly flow in suppressing it.

2. The relation of storm path to the upper-level pattern (see Figure 40 where

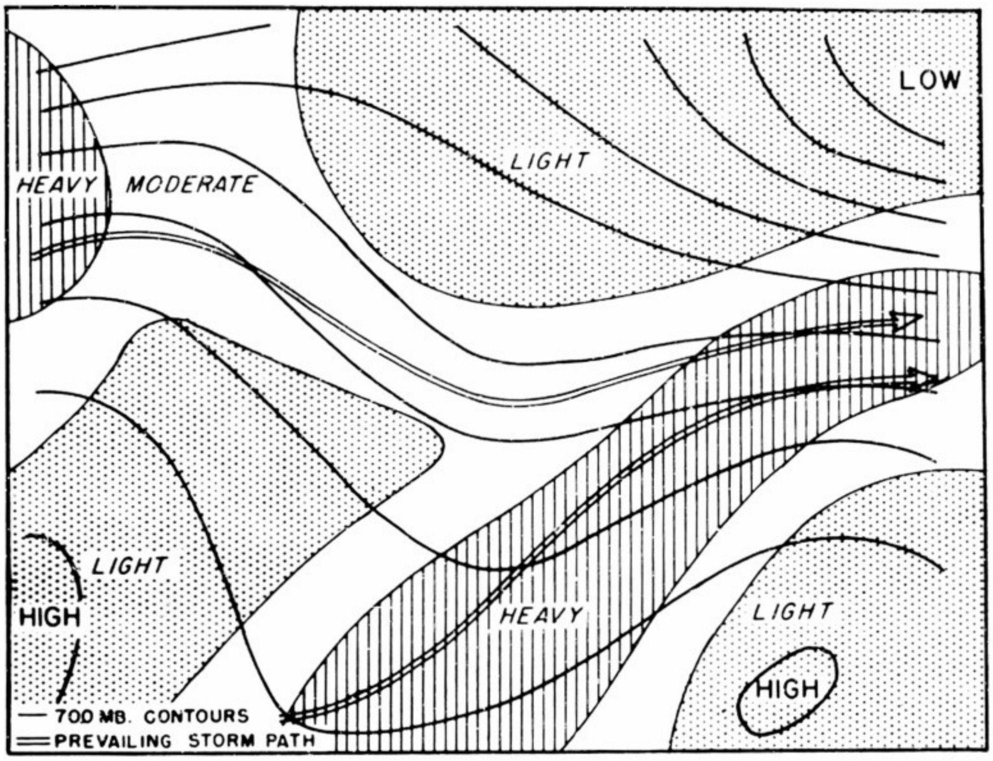


Figure 40. A schematic model (after Klein, 1948) showing the relation of precipitation areas and storm paths to the upper-level wave pattern in winter. (Klein [36])

double lines with arrows indicate average storm paths). Storms were found to be frequent in troughs tilting from southwest in lower latitudes to northeast in higher latitudes and in regions of strong confluence of warm and cold air flow (right portion of Figure 40).

3. The relation between precipitation and the position of the precipitation pattern relative to the upper-level wave pattern. Heavy precipitation is most frequent about one half the distance from the trough to the next ridge downstream; light precipitation is most frequent about halfway from the ridge to the next trough downstream.

The general applicability of the schematic model in other portions of the eastern United States has been demonstrated by experience.

More recently, Martin and Hawkins [44] have extended the research on precipitation by considering many stations throughout the United States. They have averaged 700-mb five-day mean charts for non-consecutive maps of extreme variabilities in winter precipitation for several stations throughout North America (Figure 41).

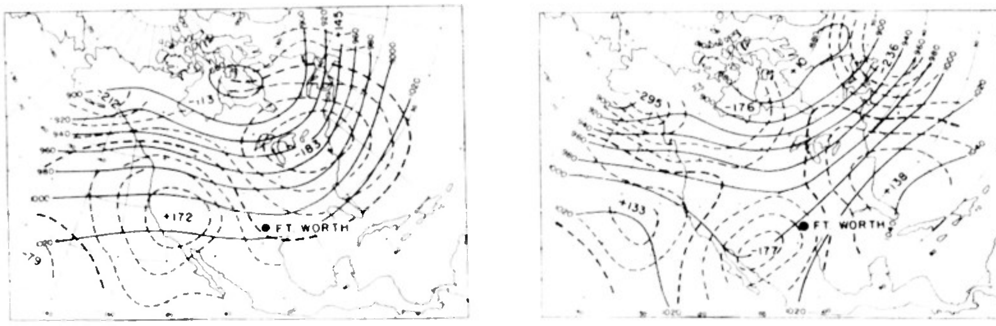


Figure 41. Composite "wet" and "dry" maps for Ft. Worth, Texas. "Wet" map is at left. (Martin and Hawkins [44]).

These show, in general, that there are two widely separated areas for each station where the 700-mb height anomalies appear to be most indicative of the precipitation anomalies. To date, these findings have not been incorporated into an objective technique. They are, however, currently being used as reference maps, or types, from which a subjective estimation of the precipitation anomalies can be made from the 700-mb mean patterns.

4. Predicting Trends Within the Forecast Period. Despite the low level of skill found in highly detailed, day-by-day forecasts of weather beyond three or four days in advance, the demand for detailed weather forecasts for extended periods is sufficiently great that an attempt is made, through prognostic charts prepared for six days in advance, to outline these day-by-day conditions. Such predictions are made not with the belief that the individual prognostic charts possess striking accuracy, but rather that, as a unit, they afford an effective, diagrammatical method of portraying sequences of idealized frontal developments, types of air-mass distributions, regions where cyclones and anticyclones are expected to stagnate or develop, and other anticipated weather trends within the forecast period (Figure 42).

In view of current needs for extended forecasts, a discussion of the generalized rules used in the construction of the daily series of maps will be presented. It should be stressed, however, that although consulting the prognostic chart for a given day may be the quickest and simplest method of obtaining an extended forecast, indiscriminate usage can also be the best way to mislead the military planner.

It will be remembered that in the forecast routine, primary consideration is given to the 700-mb five-day mean chart. The remaining predictions are dependent on and must be consistent with this upper-level prognosis. For example, the anomalies of temperature and precipitation are estimated directly from this chart. Likewise, the five-day mean sea-level prognosis is constructed primarily by mechanical techniques from the 700-mb five-day mean prognosis. To aid in this construction, the

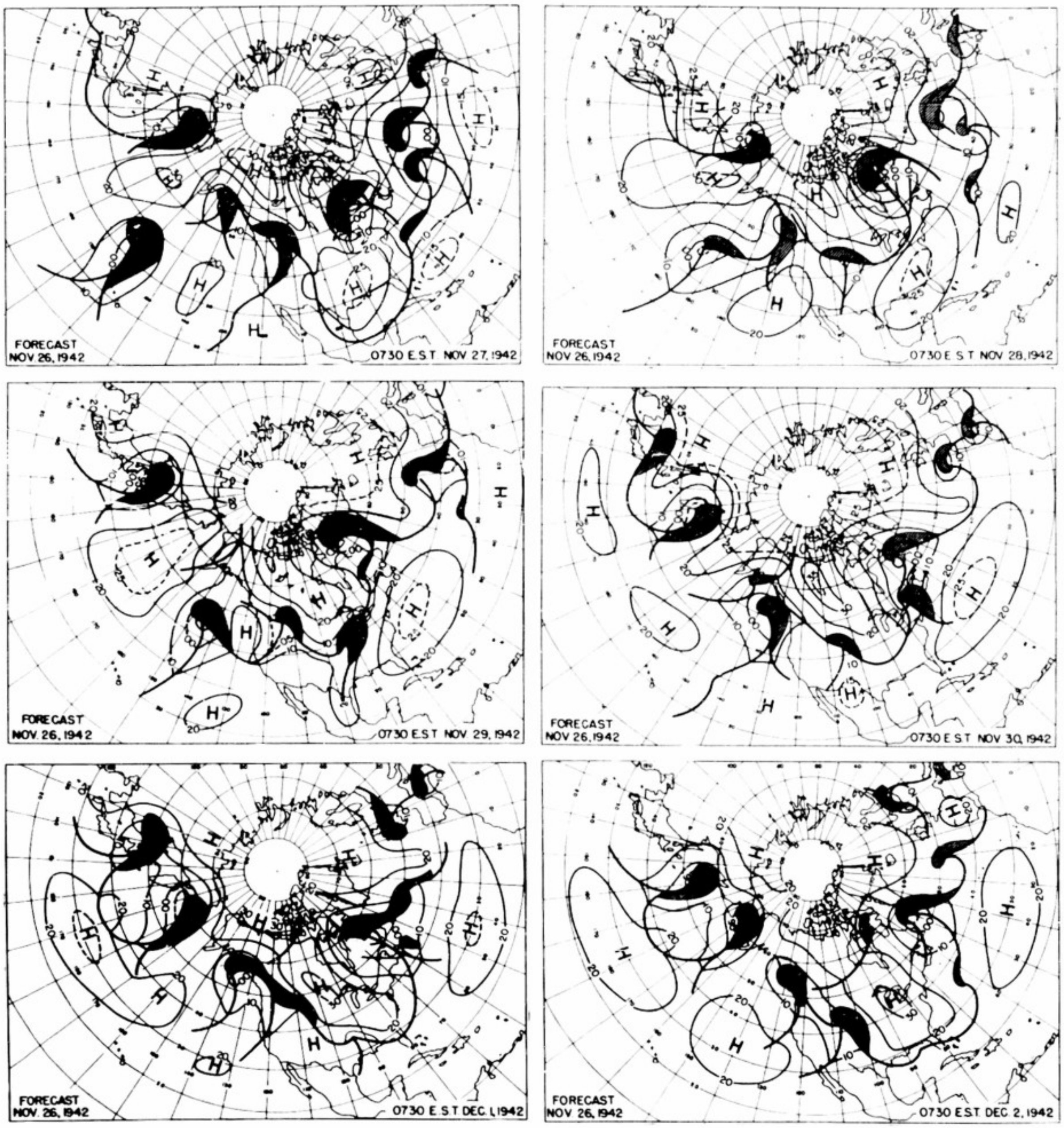


Figure 42. Series of daily prognostic charts prepared for the period 27 November to 2 December 1942. [53]. (Alternate isobars on original charts have been omitted.)

normal thickness (700-1000 mb) values are subtracted from the upper-level prognosis to obtain prognostic pressure. In analyzing the computed five-day mean pressure values, modifications are made in accordance with the anticipated mean thickness (mean virtual temperature) anomalies. Since the anomalies of mean virtual and surface temperatures are very highly correlated (Rowe [69]) this final procedure also becomes relatively objective through the use of conversion tables.

Utilizing the mean chart, one has reasonable clues as to the appearance and location of major pressure centers of the mid-period daily map. Thus the general pattern of the 96-hour prognostic chart, fourth day, has been established, whe the official forecaster finished his five-day mean sea-level prognosis. Obviously this concept is not infallible, and discretion must be used, for example, where two fairly weak, closely-spaced daily troughs constitute a single trough on the five-day mean sea-level map. In these cases the corresponding mean trough is usually located between the two daily ones.

In the construction of the fourth-day chart it is also necessary to allow for the variability between daily and mean charts (i.e., tighter gradients on the daily charts), and to show the frontal configurations which by logical continuity from the 24-hour prognosis are located in the mean centers of action. This continuity is decided upon in a discussion between the forecaster who has made the mean pattern, precipitation, and temperature forecasts; the 24-hour forecaster; and the forecaster preparing the five daily prognostic maps. At this conference various methods of making up the series are considered, and pressure centers, fronts, etc., are chosen from the 24-hour prognosis which are expected to make up the fourth day's prognosis (mean sea-level prognostic maps). The 48- and 72-hour forecasts are transitional between the short (24-hour) and the long-period forecast (96-hour). In making the transitional maps it is often necessary to develop new storms or eliminate old ones in accordance with the mean forecast. The timing and choice of systems under these circumstances are probably the most elusive steps in long-period forecasting.

The fifth and sixth days of the series of maps are constructed in conformance with the mean forecast, following logical continuity from the four previous maps. Transitions which are expected to occur in the mean state during the latter half of the period are also considered in the construction of these maps.

In the construction of the various daily maps, transitory storms are steered in accordance with the prognostic 700-mb contour pattern, and cyclones are allowed to deepen, move slowly, stagnate, or new waves to develop, in the region occupied by the prognostic mean trough. They are likewise filled, moved rapidly, or, in some cases, eliminated in regions occupied by a prognostic mean ridge. The reverse is true for transitory anticyclones. The source regions of the prognostic air masses, the contrasting temperature gradients, and the associated character of precipitation are governed by the prognostic temperature and precipitation anomalies. In addition, consideration is given to the latest daily airmass structure, the thickness (1000-700 mb) fields, and computations of constant-absolute-vorticity trajectories on the latest 700-mb and 500-mb maps. In other words, every available forecast technique, both short and long period, is used in the construction of the daily charts. They therefore represent what is considered to be the best combined estimate of numerous forecasters as to the trends within the forecast period.

To aid in the prediction of the most likely intensities of systems, and to

discourage the forecasting of highly improbable ones, bi-monthly histograms of the frequency distribution of the observed intensities of cyclones and anticyclones have been computed for numerous geographical locations throughout the northern hemisphere (Figure 43). These are used as a guide in the construction of the daily series of maps. The positions and intensities of the prognostic five-day mean sea-level centers are compared with the frequency distribution diagrams, and appropriate modifications in the normal intensities of the daily centers are made to allow for the pressure abnormalities of the mean forecast. For example, if the prognostic mean calls for below-normal pressure in an area, the series of daily maps will portray more intense storm centers than those shown by the normal distribution graphs.

Another check used in the construction of this series of daily maps is that, with a reasonable tolerance, the average of the pressures at any point on the daily maps of the five-day forecast period must equal the five-day mean sea-level prognostic values.

5. Remarks on Using the Forecast. The following points should be remembered in the use of the series of five-daily charts of the extended forecast:

a. The most accurate items portrayed by the daily series (and also on the mean charts) are the primary cyclone and anticyclone paths. This information can be used to determine optimum regions for military operations.

b. Relatively accurate results are attained in predicting the type of activity, that is to say, whether pressure centers will be weak or intense, stagnant or fast-moving. These elements may be of great value in planning military operation in the areas affected.

c. The prevailing wind directions indicated on the series of daily charts as well as on the mean patterns is fairly accurate and particularly useful in forecasting for aircraft operations.

d. Areas of above and below normal temperatures can be successfully inferred from the series. It is preferable, however, to examine the mean-temperature forecast for this information since the daily series is drawn to conform with the mean predictions. Similar arguments pertain to forecasts of total precipitation in the period.

e. "Blocking" activity, a phenomenon which disrupts the normal westerly circulation and causes radical displacements of normal storm tracks because it "holds back" cyclones in certain areas, is usually forecast fairly accurately and is readily evident from the series.

f. The weakest part of the series, though most frequently utilized, is the timing of frontal passages and other sequences within the forecast period. The series is not intended to be used for accurate estimates of the weather at any given instant during the period. Furthermore, since no successful techniques have thus far been developed to give accurate detail in the timing of frontal passages or precipitation more than three days ahead, the series should not be used for this purpose; even the third day should be considered with reservation.

At times it may be apparent, from later observed maps, that the timing of the

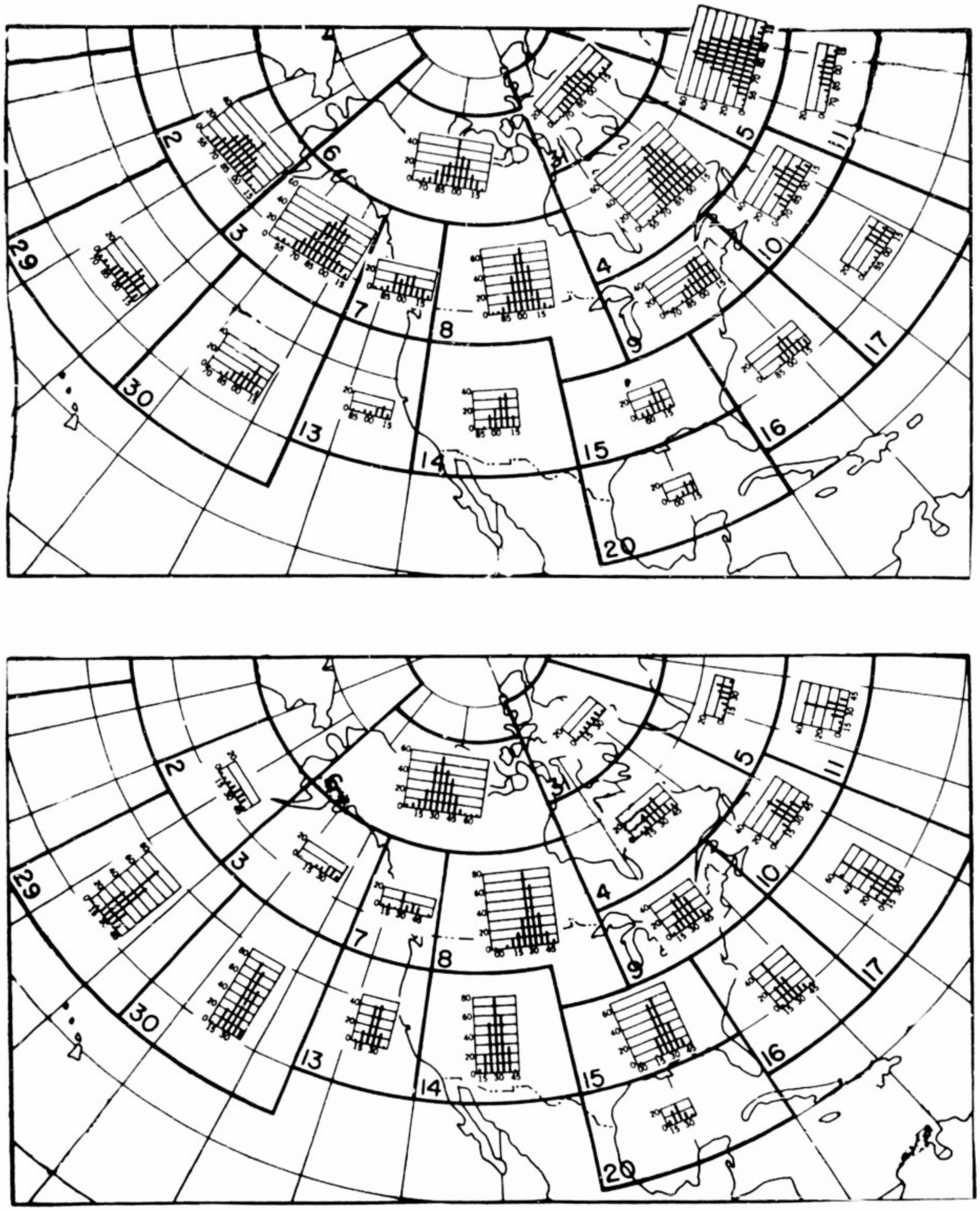


Figure 43. Frequency of intensity of cyclones (top) and anticyclones (bottom) in certain areas during November and December. (Namias [53])

activity on the series of daily prognostic charts is poor, although the general type of activity has been correctly forecast. In other cases it may be evident that certain errors in the 24-hour prognostic chart (first map) are being carried along on the sequence of prognostic charts, or that the wrong systems were chosen from the short-period forecast to make a correct mean forecast. When these cases are recognized from later data, adjustments can often be made by the short-period forecaster and some value can still be derived from the corrected series of daily prognostic charts.

Again, there are cases when one can recognize basic errors in the mean prognosis from later observed maps. Adjustments must be made with extreme care since, by the techniques currently employed, it is possible for a forecast which is apparently following the wrong weather trends to conform to the actual situation at some later date. Some of the warning signals that the 700-mb mean forecast pattern needs adjustments may be the rapid deepening of a daily cyclonic area or the stagnation of a cold low or frontal system in a location far removed from the prognostic mean trough (particularly in the region of the prognostic ridge), rapid anticyclogenesis or stagnation of a warm high in the region of the prognostic mean trough, or other types of daily activity that cannot possibly be reconciled with the mean forecast. Once these conditions are recognized, major adjustments are needed in all phases of the extended-period forecast.

The mean charts, together with techniques discussed on the preceding pages, can be utilized by the short-period forecaster in the preparation of his own short-period prognostic maps. Further, the mean temperature and precipitation forecasts for the United States can be used as guides in estimating the characteristics of migratory air masses and the type, frequency, and extent of precipitation over the country. In fact, consideration of the mean-circulation and related techniques will expand the forecaster's horizon in space and time. Study of the large-scale features and broad trends in the atmosphere will inevitably lead to improvements in short-period predictions as well as to better interpretations of extended-period forecasts [57].

6. 30-Day Forecasts. The Weather Bureau has also been making semi-monthly thirty-day forecasts for the past ten years, using methods similar to those employed in preparing the five-day forecasts [107]. The mean charts used, however, cover a thirty-day period, and their tendencies are for a ten-day period. Verification of the derived temperature and precipitation forecasts indicate some skill over a climatological forecast, especially for the temperature forecasts.

REFERENCES

1. Abbot, C. G., 1935: "Solar radiation and weather studies." Smith. Misc. Coll., 94, No. 10, 89 pp.

2. Abbot, C. G., 1944: "Solar variations and weather." Smith. Inst. Annual Report: pp. 119-53.

3. Abbot, C. G., 1947: "The sun's short regular variation and its large effects on terrestrial temperature." Smith. Misc. Coll., 107, No. 4, 33 pp.

4. Aime, E. A., and Johnson, E. C., 1943: Methods for the preparation of six-day forecasts. U. S. Wea. Bur., Nov. 1943, 26 pp.

5. Asknazy, A. E., 1936: "On the question of long-range weather forecasting methods." Met. and Hydr. (Moscow), 1948, No. 10; 3-40, and No. 11: 3-43. (In Russian)

6. Brezowsky, H. and Hess, P., 1952: "Katalog der grosswetterlagen Europas." Berichte der Deutscher Wetterdenst in der U.S.-Zone. No. 33. (English translation available from ASTIA as AD-12720.)

7. Baur, F., 1947: Musterbeisbiele eurobaischer Grosswetterlagen. Wiesbaden, Dieterich.

8. Baur, F., 1948: Einführung in die Grosswetterkunde. Wiesbaden, Dieterich, 1654 p.

9. Baur, F., 1951: "Extended-range weather forecasting." Compendium of Meteorology., pp. 814-833.

10. Bliss, E. W., 1928: "The Nile flood and world weather." Mem. Roy. Met. Soc., Vol. 1, No. 5: 79-85.

11. Bortman, R. S., 1948: "Empirical corrections to constant absolute vorticity trajectories." Transactions Amer. Geophy. Union, No. 3:324.

12. Bowie, E. H., and Weightman, R. H., 1914: "Types of storms of the U.S. and their average movements." Mo. Wea. Rev. Suppl. No. 1.

13. Brennecke, W., 1904: "Beziehungen Zwischen der Luftdruckverhaltung und der Eisverhaltnisse des Ostgronlandischen Meere." Ann. d. Hydr. Vol. 32: 49-62.

14. Brier, G. W., 1942: Verification of prognostic pressure patterns. Extended Forecast Div., U. S. Wea. Bur.

15. Brooks, C. E. P., and Quennel, W. A., 1928: "The influence of Arctic ice on the subsequent distribution of pressure over the Eastern North Atlantic and Western Europe." Meteor. Office, Geophys. Mem. No. 41.

16. Brooks, C. E. P., 1930: "The role of the oceans in the weather of Western Europe." Q.J.R. Met. Soc., pp. 131-140.

17. Brooks, C. E. P., 1946: "Annual Recurrences of Weather: Singularities." Weather, Vol. 1: 107-113, 130-134. (August and September)

18. Buchan, A., 1869: Interruptions in the regular rise and fall of temperature in the course of the year, as shown by observations made in Scotland during the past 10 years, 1857-1866. J. Scot. Met. Soc., Vol. 2, New Series, 1867-69: Pt. I: 4-15; Pt. II: 41-50; Pt. III: 107-112.

19. Calif. Institute of Technology Meteor. Department, 1943: Synoptic Weather Types of North America. Meteor. Dept. Rep., Calif. Inst. of Tech.

20. Charney, J., and Eliassen, A., 1949: "A numerical method for predicting the perturbations of the middle latitude westerlies." Tellus, Vol. 1, No. 2: pp. 38-54.

21. Clayton, H. H., 1923: World Weather. N. Y.: The MacMillan Co., pp. 215-69.

22. Clayton, H. H., 1936: "Long period weather changes and methods of forecasting." Monthly Wea. Rev., Vol. 64, pp. 359-76.

23. Cressman, G. P., 1948: "On the forecasting of long waves in the upper westerlies." J. Meteor., Vol. 5, No. 2, pp. 44-57.

24. Darling, D. A., 1944: Relationship between the analogue forecast and other methods of forecasting. Cal. Inst. Tech.-AAF Res. Unit, Rpt.

25. Elliott, R. D., 1944: Weather forecasting by weather type methods. U. S. Navy Dept., Long range Weather Forecasting Unit, Washington, D. C., 55 pp.

26. Elliott, R. D., 1949: "Forecasting the weather." Weatherwise, Vol. 2: pp. 15-18, 40-43, 64-67, 86-88, 110-113, 136-138.

27. Elliott, R. D., 1950: "Extended-range forecasting by weather types." Compendium of Meteorology., pp. 834-840.

28. Fawcett, E. B., 1949: The seven-day forecasting method. U. S. Wea. Bur., (manuscript).

29. Flohn, Herman, 1942: "Kalendermassige Bindungen im Wettergeschehen." Naturwissenschaften, Vol. 30, Nos. 48 and 49: pp 718-728 (Nov. 27)

30. Fultz, D., 1945: "Upper-air trajectories and weather forecasting." Univ. of Chicago, Misc. Reports No. 19.

31. Groissmayr, F., 1926: "Correlation between Argentine pressure and temperature in U. S. six months later." Mo. Wea. Rev., Vol. 54, p. 299.

32. Groissmayr, F., 1930: "Relations between winters in Manitoba and the following spring in Eastern U. S." Mo. Wea. Rev., Vol. 58, p. 246.

33. Haurwitz, B., 1940: "The motion of atmospheric disturbances on the spherical earth." J. Mar. Res., Vol. 3: pp. 254-267.

34. Haurwitz, B., 1944: "Final report on the use of symmetry points in the pressure curves for long-range forecasts." USAF Air Weather Service Technical Report 105-7.

35. Johnson, C. B., 1944: "Some relationships between five-day mean sea-level maps and their component daily maps." Reports on Extended Forecasting Research, U. S. Wea. Bur.

36. Klein, W. H., 1948: "Winter precipitation as related to the 700-mb circulation." Bull. Amer. Met. Soc., Vol. 29: 439-453, (November).

37. Klein, W. H., 1948: Application of the regression method to monthly forecasts. Unpub. Rpt. in Ext. Forecast Sec., U. S. Wea. Bur.

38. Klein, W. H., 1949: "The unusual weather and circulation of the 1948-49 winter." Mo. Wea. Rev., Vol. 77, pp 99-113 (April).

39. Klein, W. H., 1950: The projected tendency and extended height. Unpub. Rpt. of Ext. Forecast Sec., U. S. Wea. Bur., 22 pp.

40. Klein, W. H., 1951: An empirical study of long waves on monthly mean charts in North America during winter. Unpub. report of Ext. Forecasting Sec. of U. S. Wea. Bur.

41. Krick, I. P., 1942: A dynamical theory of the atmospheric circulation and its use in weather forecasting. Met. Dept. Calif. Inst. of Tech., 43 pp.

42. MacPherson, H. G., 1940: "Accuracy of Smithsonian Institution solar constant measurements," in: "Reports on critical studies of methods of long-range weather forecasting," Mo. Wea. Rev., Suppl. No. 39, pp. 98-117.

43. Martin, D. E. and Leight, W. G., 1949: "Objective temperature estimates from mean circulation patterns." Mo. Wea. Rev., Vol. 77: pp. 275-283.

44. Martin, D. E. and Hawkins, H. F., 1950: "The relationship of temperature and precipitation over the U. S. to the circulation aloft." Weatherwise, Vol. 3.

45. Montgomery, R. B., 1940: "Report on the work of G. T. Walker," in: Monthly Weather Review, Supplement 39. pp. 1-22.

46. Multanovski, B. P., 1915: "The influence of centers of action of the atmosphere on the weather in European Russia during the warm season." Recueil de Geophysique, Vol. 2, No. 3: pp. 73-97. (in Russian).

47. Multanovski, B. P., 1920: "Basic considerations for division of European Russia into districts according to the activities of the Polar Center of action of the atmosphere." Bull. of the Centr. Geophys. Obs., Vol. 1, No. 3: 31-35. (Leningrad) (In Russian)

48. Multanovski, B. P., 1924: "Northeast storms on the Black Sea and their significance for the synoptic situation of Europe." Bull. of the Centr. Hydromet. Bur., No. 3: 45-54. (In Russian)

49. Multanovski, B. P., 1933: "The present (1933) status of development of long-range weather forecasting methods in U.S.S.R." Met. Vestnik, Vol. 43, Nos. 5-7: pp. 129-143. (In Russian)

50. Namias, J., and Clapp, P. F., 1942: Use of trend methods in forecasting 5-day mean pressure charts. U. S. Wea. Bur., 45 pp.

51. Namias, J., and Clapp, P. F., 1944: "Studies of the motion and development of long waves in the Westerlies." Jour. of Meteor., Vol. 1, Nos. 3 and 4 (December).

52. Namias, J., and Clapp, P. F., 1946: "Normal fields of convergence and divergence at the 10,000-foot level." Jour. of Meteor., Vol. 3, No. 1 (March).

53. Namias, J., 1947: "Extended forecasting by mean circulation methods." U. S. Wea. Bur., 89 pp.

54. Namias, J., 1948: "Evolution of monthly mean circulation and weather patterns." Tran. Amer. Geophys. Union, Vol. 29: pp. 777-88 (December).

55. Namias, J., and Clapp, P. F., 1951: "Observational studies of general circulation patterns," in: Compendium of Meteorology, pp. 551-568.

56. Namias, J., 1951: "General aspects of extended-range forecasting." Compendium of Meteorology, pp. 802-813.

57. Namias, J., 1951: General circulation of the upper troposphere and lower stratosphere. U. S. Wea. Bur. (Manuscript)

58. Norton, H. W., Brier, G. W., and Allen, R. A., 1944: "A project to test the potential usefulness of pressure patterns for forecasting," in: Reports on Extended Forecasting Research, U. S. Wea. Bur.

59. Pagava, S. T., et al., 1940: Basic principles of the synoptic method of long-range weather forecasting. Osnovy sinopticheskovo methoda dolgostochnykh prognozov pogody. Leningrad, U.S.S.R.: Hydrometeor. Publ. House. 3 Vols., Transl. by Wea. Inf. Serv., Hq., Army Air Forces, 1943.

60. Page, L. F., et al., 1940: "Reports on critical studies of methods of long-range weather forecasting." Mo. Wea. Rev., Supp. No. 39. 130 pp.

61. Page, L. F., 1940: "Some statistical tests of solar constant-weather relationships." Mo. Wea. Rev., Suppl. No. 39. pp. 121-25.

62. Patterson, J., 1931: "Water temperatures on the Pacific and their effect on the weather of Canada." Proceedings of the Fifth Pacific Science Congress, Canada, Vol. III, p. 126.

63. Petterssen, Sverre, 1940: Weather analysis and forecasting. New York: McGraw-Hill.

64. Reed, Chas. D., 1925: "Monthly forecasts by correlation." Mo. Wea. Rev., Vol. 53, pp. 249-51.

65. Reed, T. R., 1932: "Weather types of the northeast Pacific Ocean as related to the weather on the north Pacific coast." Mo. Wea. Rev., Vol. 60, pp. 246-52.

66. Rossby, C. G., 1939: "Relation between variations of the zonal circulation of the atmosphere and the displacement of the semi-permanent centers of action." Journ. of Marine Research, Vol. 2: pp. 38-55.

67. Rossby, C. G., 1942: "Kinematic and hydrostatic properties of certain long waves in the westerlies." Report No. 5, Univ. of Chicago, Inst. of Meteorology. 37 pp.

68. Rossby, C. G., 1945: "On the propagation of frequencies and energy in certain types of oceanic and atmospheric waves." J. Meteor., Vol. 2, pp. 187-204.

69. Rowe, W. M., 1944: "Relationship between surface temperature and mean virtual temperature in the lower troposphere." Res. Paper No. 22, U. S. Wea. Bur.

70. Schell, I. I., 1940: "Baur's Contribution to Long-Range Weather Forecasting." Mo. Wea. Rev., Suppl. No. 39: pp. 63-87.

71. Schell, I. I., 1940: "A preliminary Summary of the Multanovski School of Long-Range Forecasting." Mo. Wea. Rev., Suppl. No. 39: pp. 92-96.

72. Schell, I. I., 1940: "Polar ice as a Factor in Seasonal Weather." Mo. Wea. Rev., Suppl. No. 39; pp. 27.

73. Schell, I. I., 1947: "Dynamic Persistence and its applications to long-range foreshadowing." Harvard Meteor. Studies, No. 8; 80 pp.

74. Schmauss, A., 1938: "Synoptische Singularitäten." Met. Zeit., Vol. 55, pp. 385-403.

75. Smagorinsky, M., and Brier, G. W., 1949: "Verification of temperature prediction based on an alleged periodicity in solar radiation." Bull. Amer. Meteor. Soc., Vol. 30: pp. 256-57.

76. Smith, K. E., 1942: Five-day precipitation patterns in the U. S. in relation to surface and upper air mean charts. Unpub. thesis for the Master's Degree at Mass. Inst. of Tech., May 1941, expanded Dec. 1942.

77. Stone, E. S., and H. C. Willett, 1944: Report of the progress of research leading to the improvement of the present methods of extended weather forecasting and the development of new methods. MIT, Dept. of Meteor.

78. USAF, Hq., AWS: "Weather forecasting by statistical and synoptic extrapolation." AAF, Wea. Div. Rpt. 730 (1944); also: Wea. Serv. Bull. No. 5 1950.

79. USAF, Air Weather Service Bulletin No. 5, 1950: "Regional dynamic analogue project under way." pp. 15-18. (Extract from Geophysiske Publikasjoner, Vol. 17, No. 9: pp. 1-28).

80. Vital, L. A., 1948: Meteorologiia i Gidrologiia, No. 4.

81. Wadsworth, G. P., 1948: "Short range and extended forecasting by statistical methods." Air Weather Technical Report 105-38.

82. Wahl, E., 1939: "Eine Erweiterung des Begriffes der Symmetrie von Luftdruckkurven." Meteorologische Zeitschrift, Vol. 56, pp. 445-52.

83. Walker, G. T., 1910: "Correlation in seasonal variations of weather, II." Memoirs of the India Meteorological Dept. 21, Part II: pp. 22-45.

84. Walker, G. T., 1922: "Correlation in seasonal variations of weather, VII. The local distribution of monsoon rainfall." Memoirs of the India Meteorological Dept., Vol. 23: pp. 23-39.

85. Walker, Sir Gilbert, 1924: "Correlation in seasonal variation of weather." Indian Met. Mem. No. 24, Part IX, pp. 275-332. (See Abstract in Mo. Wea. Rev., Vol. 53, pp. 252-54.)

86. Walker, G. T., 1924: "Correlation in seasonal variations of weather, X. Applications to seasonal forecasting in India." Memoirs of the India Meteorological Dept., Vol. 24: pp. 333-45.

87. Walker, G. T., 1928: "World Weather." Quart. Journ. of the Roy. Met. Soc., Vol. 56: pp. 79-87.

88. Walker, Sir Gilbert and Bliss, E. W., 1930: "Some applications to seasonal foreshadowing. World Weather IV." Mem. Roy. Met. Soc., Vol. 3, No. 24, pp. 81-95.

89. Walker, G. T., 1933: "Seasonal weather and its prediction. British Association for the Advancement of Science, Report 103: 25-44.

90. Walker, G. T., and Bliss, E. W., 1937: "World Weather VI." Memoirs of the Royal Meteorological Society, Vol. 4: pp. 119-39.

91. Walker, G. T., and C. E. P. Brooks, 1944: Investigations of symmetry point techniques. (Unpublished)

92. Weber, J. H., 1934: "Alaska pressure may indicate New York temperatures." Bull. Amer. Met. Soc., Vol. 15, pp. 284-5.

93. Weeks, J. R., 1932: "Correlation between winter and succeeding summer weather." Bull. Amer. Met. Soc., Vol. 13, p. 183.

94. Weickmann, L., 1930: "Die Dominierende Luftdruckwelle des Strengen Winters 1928/29." Zeitschrift für Geophysik, Vol. 6, pp. 291-96.

95. Weickmann, L., 1931: "Neuere Ergebnisse aus der Theorien der Symmetriepunkte." Gerlands Beitrage zur Geophysik, Vol. 34, pp. 244-51.

96. Weightman, R. H., 1941: "Preliminary studies in seasonal weather forecasting." Mo. Wea. Rev. Suppl. No. 45. 9? pp.

97. Wexler, H., 1950: "Possible effects of ozonosphere heating on sea-level pressure." Journ. of Meteorology, Vol. 7: pp. 370-381.

98. Willett, H. C., 1940: "Review of H. H. Clayton on long-range weather changes and methods of forecasting," in: "Reports on critical studies of methods of long-range weather forecasting," Mo. Wea. Rev. Suppl. No. 39, pp. 126-30.

99. USAF, Hq, AWS, 1951: "Comparison of Analogue Selection Methods." Air Weather Service Technical Report 105-70.

100. McEwen, George F., 1934: "Methods of seasonal weather forecasting at the Scripps Institution of Oceanography," Bull. of the American Meteorological Society, Vol. 15, pp. 249.

101. Flohn, Herman and Hess, Paul, "Singularities of large scale meteorological conditions over the course of a year in the trend of weather conditions for Central Europe (Statistical-Synoptical Examination 2)" Meteorologische Rundschau, Vol. 2, No. 9-10, September-October 1949. (English translation available from ASTIA as ATI-164763).

102. USAF, Hq. AWS, 1953: "A method for the preparation of four-day surface and 500-mb prognostic charts." 2058th Air Weather Wing Technical Bulletin, pp. 36-44. (October).

103. USAF, Hq, AWS, 1952: "Tables for computing constant absolute vorticity trajectories." Air Weather Service Technical Report 105-99 (December).

104. USAF, Hq, AWS, 1953: "Forecasting the long waves in the upper westerlies." Air Weather Service Technical Report 105-90 (May).

105. Bartels, J., 1948: "Anschauliches uber den statistischen Hintergrund der sog. Singularitaten im Jahresgang der Witterung." Ann. Met. p. 106 ff. Reply by Muller-Anner, H., (1950): "Uber den statistischen Hintergrund der Singularitaten," Ann. Met., pp. 107-115.

106. Wahl, E., 1952: "The construction and application of contingency tables in weather forecasting." Air Force Surveys in Geophysics No. 19. Geophysics Research Directorate, Air Force Cambridge Research Center, Air Research and Development Command.

107. Namias, J., 1953: "Thirty-day forecasting: A review of a ten-year experiment." Meteorological Monographs, No. 6. American Meteorological Society (July).

108. Ehrlich, A. E., 1954: "Synoptic patterns associated with singularities in the Northeast Atlantic," To appear in the Bull. of the AMS.

Air Force-WAFB-Mass